REVIEW ARTICLE

Sports Med 2009; 39 (6): 469-490
0112-1642/09/0006-0469/$49.95/0

Lactate Threshold Concepts
How Valid are They?

Oliver Faude,[1,2] *Wilfried Kindermann*[2] and *Tim Meyer*[1,2]

1 Institute of Sports Medicine, University Paderborn, Paderborn, Germany
2 Institute of Sports and Preventive Medicine, University of Saarland, Saarbrücken, Germany

Contents

Abstract

During the last nearly 50 years, the blood lactate curve and lactate thresholds (LTs) have become important in the diagnosis of endurance performance. An intense and ongoing debate emerged, which was mainly based on terminology and/or the physiological background of LT concepts. The present review aims at evaluating LTs with regard to their validity in assessing endurance capacity. Additionally, LT concepts shall be integrated within the 'aerobic-anaerobic transition' – a framework which has often been used for performance diagnosis and intensity prescriptions in endurance sports.

Usually, graded incremental exercise tests, eliciting an exponential rise in blood lactate concentrations (bLa), are used to arrive at lactate curves. A shift of such lactate curves indicates changes in endurance capacity. This very global approach, however, is hindered by several factors that may influence overall lactate levels. In addition, the exclusive use of the entire curve leads to some uncertainty as to the magnitude of endurance gains, which cannot be precisely estimated. This deficiency might be eliminated by the use of LTs.

The aerobic-anaerobic transition may serve as a basis for individually assessing endurance performance as well as for prescribing intensities in

endurance training. Additionally, several LT approaches may be integrated in this framework. This model consists of two typical breakpoints that are passed during incremental exercise: the intensity at which bLa begin to rise above baseline levels and the highest intensity at which lactate production and elimination are in equilibrium (maximal lactate steady state [MLSS]).

Within this review, LTs are considered valid performance indicators when there are strong linear correlations with (simulated) endurance performance. In addition, a close relationship between LT and MLSS indicates validity regarding the prescription of training intensities.

A total of 25 different LT concepts were located. All concepts were divided into three categories. Several authors use fixed bLa during incremental exercise to assess endurance performance (category 1). Other LT concepts aim at detecting the first rise in bLa above baseline levels (category 2). The third category consists of threshold concepts that aim at detecting either the MLSS or a rapid/distinct change in the inclination of the blood lactate curve (category 3).

Thirty-two studies evaluated the relationship of LTs with performance in (partly simulated) endurance events. The overwhelming majority of those studies reported strong linear correlations, particularly for running events, suggesting a high percentage of common variance between LT and endurance performance. In addition, there is evidence that some LTs can estimate the MLSS. However, from a practical and statistical point of view it would be of interest to know the variability of individual differences between the respective threshold and the MLSS, which is rarely reported.

Although there has been frequent and controversial debate on the LT phenomenon during the last three decades, many scientific studies have dealt with LT concepts, their value in assessing endurance performance or in prescribing exercise intensities in endurance training. The presented framework may help to clarify some aspects of the controversy and may give a rationale for performance diagnosis and training prescription in future research as well as in sports practice.

1. Historical Remarks on Endurance Performance Diagnosis

As early as 1808, Berzelius observed that lactic acid was produced in the muscles of hunted stags.[1] About a century later, several scientists studied the biochemistry of energy metabolism and muscle contraction in more detail. This led to a much deeper understanding of the formation of lactic acid (lactate and hydrogen ions) during intense exercise.[2-5] At that time, it was common belief that lactic acid is a waste product of glycolysis and will be formed when oxygen delivery to exercising muscles is not sufficient and muscle anaerobiosis occurs.[2,6,7] This view has been challenged considerably during the last two decades. Anaerobic glycolysis and, thus, lactate kinetics rather seem to be an ongoing process – even in the resting individual – which is highly related to the metabolic rate but not necessarily to oxygen availability (for detailed review see Gladden,[1,8] Brooks,[9] Robergs et al.[10]).

In the first half of the 20th century the concept of maximum oxygen consumption as the first and probably most common means of evaluating aerobic endurance capacity was developed by the working group of Nobel Laureate AV Hill.[6] maximal oxygen uptake ($\dot{V}O_{2max}$) has been established as a valuable tool to distinguish between fit and unfit subjects. However, several concerns were raised regarding the sensitivity of $\dot{V}O_{2max}$. For instance, it is difficult to discriminate

between subjects of homogenous performance levels by means of $\dot{V}O_{2max}$.[11-18] In addition, sufficient effort during whole-body work and, therefore, adequate motivation of the investigated subject is necessary to appropriately determine $\dot{V}O_{2max}$. Particularly in clinical settings with diseased patients, whole-body exhaustion is difficult to attain or is even avoided because of the risk of adverse events.[19,20]

Therefore, attempts have been made to establish sub-maximal parameters to assess cardiorespiratory fitness in patients and athletes. Early research by the working group of Hollmann established the so-called 'point of optimum ventilatory efficiency' corresponding to the first increase in the ventilatory equivalent of oxygen and of arterial lactate concentrations during incremental exercise.[19,21] A few years later, Wasserman and McIllroy[22] determined this intensity by plotting ventilation versus oxygen uptake in cardiac patients and named it the 'anaerobic threshold' (LT_{An}). At that time, routine determination of blood lactate concentrations (bLa) was associated with several difficulties and gas exchange measurements were more common – especially in clinical settings. Therefore, it became popular to detect the LT_{An} by means of gas exchange analysis.

In the 1960s, the enzymatic method for measuring lactate concentrations from capillary blood samples was developed. This led to the increasing popularity of using bLa as a parameter to assess endurance capacity as well as for classifying work rate during exercise.[19,23,24] In the following years, numerous lactate threshold (LT) concepts were developed. The number of scientific studies on LTs has increased enormously up to now and the sub-maximal course of bLa during incremental exercise has probably become one of the most important means in the diagnosis of endurance performance in sports practice.[15,16,25,26] However, the variety of different threshold concepts has led to considerable confusion and misinterpretation.

An intense and ongoing debate emerged, which was mainly based upon terminology and/or the physiological background of LT concepts.[27] Early assumptions on lactate production and distribution in the organism have been challenged.[1,8-10,28] It has been argued that bLa increase continuously rather than show a clear threshold during incremental exercise. Furthermore, the contribution of aerobic and anaerobic pathways to energy production does not change suddenly but shows a continuous transition and, therefore, the term 'threshold' might be misleading.[29]

Against this background and to unravel the confusion, it seems valuable to give a summary on published LT concepts. The present review is mainly aimed at evaluating the located LT concepts with regard to their validity in assessing aerobic endurance capacity and prescribing training intensity. A further aim was to try to integrate those concepts into a framework that was originally called the aerobic-anaerobic transition.[30-32]

It has to be emphasized that this text focuses on LTs only. Although a close link between lactate and gas exchange markers has often been proposed,[21,31,33-36] there is still controversial debate with regard to the underlying physiological mechanisms.[37] A comprehensive review on gas exchange thresholds has recently been published.[31] Additionally, it is not within the scope of this article to exhaustively review the biochemistry of glycolysis and lactate metabolism.

2. Incremental Exercise Testing and the Interpretation of Blood Lactate Curves

2.1 The Entire Blood Lactate Curve

Usually, graded incremental exercise tests (GXTs) are used to evaluate aerobic endurance performance capacity. Typically, an exponential rise in bLa during incremental exercise testing can be observed (figure 1). The issue of interest is to interpret the resulting lactate curve with regard to endurance capacity. It is generally accepted that a rightward shift of the lactate curve (lower bLa at given workload) can be interpreted in terms of an improved endurance capacity[38-40] and, in contrast, a shift to the left (higher bLa at given workload) is usually considered to represent worsening endurance capacity.[41]

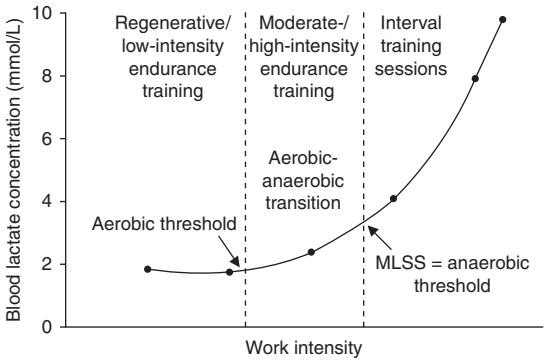

Fig. 1. A typical lactate-workload plot including the aerobic-anaerobic transition as a framework to derive endurance training intensities for different intensity zones. **MLSS** = maximal lactate steady state.

Overall lactate levels are known to be influenced by depleted glycogen stores (due to a low carbohydrate diet or preceding exhaustive exercise).[42-44] For instance, lower bLa at the same work rates have been reported in a glycogen-depleted subject compared with a subject in normal condition. This may lead to a downward shift of the lactate curve and it is important that this is not falsely interpreted as an enhancement in endurance capacity.[45] Furthermore, several other factors like muscle fibre composition, glycolytic and lipolytic enzyme activity as well as capillary or mitochondrial density might influence blood lactate curves.[46] Additionally, the entire lactate curve is dependent on several other methodological issues, which should be taken into account when interpreting test results.

2.1.1 Test Design and Data Treatment

It is of note that the specific GXT protocol can vary considerably with regard to starting and subsequent work rates, work rate increments and stage duration. A recent review focused on the influence of varying test protocols on markers usually used in the diagnosis of endurance performance.[47] For instance, varying stage duration or work rate increments may lead to relevant differences in blood lactate curves and LTs.[48-50] A possible reason might be the time allowed for lactate diffusion in the blood until the next work rate increment.[47]

In addition, there has been great debate on the best fitting procedure for the obtained bLa data set. For instance, a single-[51] or double-phase model[52] using two or three linear regression segments, a double-log model,[53] a third-order polymonial[54] or an exponential function[55] have been used in previous studies. Up to now, no generally accepted fitting procedure has been established.[47] Thus, it seems appropriate that test design as well as data fitting procedures should be chosen (and reported) as has been originally described for a certain LT.

2.1.2 Methodology of Blood Lactate Determination

From a methodological point of view, the site (earlobe, fingertip) as well as the method (venous, arterial, capillary) of blood sampling[56,57] and the laboratory methods (lactate analyser, analysed blood medium)[58-60] may also affect the test result. Samples taken from the earlobe have uniformly been shown to result in lower bLa than samples taken from the fingertip.[57,61,62] With regard to the analysed blood medium, plasma values were considerably higher than whole venous lactate concentrations, with capillary values lying in between.[48,56,63-65] In addition, several studies reported partly considerable differences between various lactate analysers (portable field vs laboratory analysers, amperometric vs photometric method) and under various climatic conditions.[58,66-69]

The analysis of the whole blood lactate curve is a very global approach to evaluating endurance capacity. On the one hand, this approach is affected by the above-mentioned factors on overall lactate levels. On the other hand, the use of the entire curve leads to some uncertainty as to the magnitude of endurance gains that cannot be precisely estimated. However, the use of LTs enables a quantitative evaluation of changes in endurance performance. In addition, the ideal LT concept would not be affected by the above-mentioned factors. There is evidence that approaches that analyse relative changes in bLa during GXTs may be favourable compared with the use of absolute lactate values in this regard.[56,67]

2.2 A Framework for Endurance Diagnosis and Training Prescriptions

In 1979, Kindermann et al.[30] introduced the concept of the aerobic-anaerobic transition as a framework for performance diagnosis and training prescription in endurance sports (figure 1). Since then, this framework has been adopted, applied and refined by several scientists either using lactate or gas exchange markers.[16,26,31,33,34,46,70-75]

This model consists of two typical breakpoints that are passed during incremental exercise. In the low intensity range, there is an intensity at which bLa begin to rise above baseline levels. This intensity was originally determined using gas exchange measurements,[21,22] and Wasserman called it the 'anaerobic threshold'. This term has since been used for various LTs, particularly those with a different physiological background,[33,75] and, thus, has caused considerable confusion. Kindermann et al.[30] and Skinner and McLellan[34] suggested this intensity be called the 'aerobic threshold' (LT_{Aer}), because it marks the upper limit of a nearly exclusive aerobic metabolism and allows exercise lasting for hours. This intensity might be suitable for enhancing cardiorespiratory fitness in recreational sports, for cardiac rehabilitation in patients or for low-intensity and regenerative training sessions in high level endurance athletes.[16,25,26,32,70,76-81]

Exercise intensities only slightly above the LT_{Aer} result in elevated but constant bLa during steady-state exercise and can be maintained for prolonged periods of time (~4 hours at intensities in the range of the first increase in bLa[82-84] and 45–60 minutes at an intensity corresponding to the maximal lactate steady state [MLSS][85,86]). Although anaerobic glycolysis is enhanced, it is speculated that such intensities may induce a considerable increase in the oxidative metabolism of muscle cells.[30,87] Theoretically, a high stimulation of oxidative metabolism for as long a period of time as is possible in this intensity range might be an appropriate load for endurance training. The highest constant workload that still leads to an equilibrium between lactate production and lactate elimination represents the MLSS. Some authors suggested that this intensity be called the 'anaerobic threshold'.[27,30,49,88]

It has been shown that the constant bLa at MLSS is not equal in all individuals and can vary considerably (values from 2 up to 10 mmol/L were reported in several studies).[50,72,86,89-93] Beneke and von Duvillard[94] as well as Beneke et al.[95] reported that bLa at MLSS is dependent on the motor pattern of exercise. Therefore, it was suggested that to determine the LT_{An}, individualized approaches rather than a fixed bLa should be used.[88,96,97]

The MLSS represents the upper border of constant load endurance training.[30,49,71,95] Intensities above the MLSS have been used to guide interval training sessions in different endurance sports.[26,31,98-102]

The intensity range between LT_{Aer} and LT_{An} is called the aerobic-anaerobic transition. The described thresholds (first increase in bLa and MLSS) have recently also been called 'lactate threshold and lactate turnpoint', 'lactate threshold and anaerobic threshold', or 'anaerobic threshold 1 and 2', respectively.[26,75,103,104] Within the present review, it was decided to stick to the originally introduced nomenclature.[30,31,34]

There has been an exhaustive debate whether there exist clear breakpoints in the lactate/work rate relationship or whether lactate increase is rather a continuous function during incremental work.[47] Furthermore, the terms 'aerobic' and 'anaerobic' threshold may suggest clearly discernible physiological processes. However, these processes are rather of a transitional nature with aerobic and anaerobic energetic pathways always simultaneously contributing to energy production during both low- and high-intensity exercise. However, the proposed model seems appropriate both from a practical and from a didactical point of view. In addition, there is evidence that the described breakpoints may have some exercise physiological relevance. It has been shown that exercise above the MLSS is associated with an over-proportional excretion of stress hormones as well as of immunological markers during constant load exercise.[105,106] Furthermore, Lucia et al.[107] observed changes in electromyographical activity of the *vastus lateralis* and

rectus femoris that were coincidental with the aerobic-anaerobic transition in 28 elite male cyclists.

The widespread use of this model as well as the absence of an accepted alternative was the rationale for using this framework in the present review to categorize published LT concepts.

3. Validation of Lactate Thresholds

3.1 Competition Performance

It is widely accepted that LTs (and the submaximal course of bLa during incremental exercise) are a criterion measure for aerobic endurance performance.[24,26,30,72,81,108] In particular, it has been shown that LTs are superior to maximal oxygen uptake when assessing endurance performance in homogenous groups of athletes.[11,12,109-111] The obvious gold standard to validate an LT concept is to compare it with the most recent competition performance in an endurance event (concurrent validity) or to assess its value in predicting endurance performance in future events (predictive validity). As an alternative to competition performance, the results of laboratory tests simulating an endurance event can be used. This might have the advantage of a higher standardization and, therefore, these test results may be more reliable. Correlations between the test value (LT) and the validity criterion (competition performance) can be dependent on several confounding factors such as, for example, the chosen competitive event (duration, laboratory or outdoor, athletic track or off-road), the sport that is evaluated as well as sex or age group and its heterogeneity in terms of endurance.

3.2 The Maximal Lactate Steady State

Endurance capacity can – from a metabolic point of view – be regarded as the highest steady state by energy supply from oxidative phosphorylation.[87] Therefore, another approach to assess aerobic endurance performance is the determination of the highest constant exercise intensity that can be maintained for a longer period of time without a continuous rise in bLa. This intensity represents the MLSS, which has been shown to be highly related to competition performance in endurance events (r [correlation coefficient] = 0.92 with 8 km running, r = 0.87 with 5 km running and r = 0.84 with 40 km cycling time trial speed, respectively).[112-114] The MLSS has been defined by some authors as the 'anaerobic threshold' because it represents an exercise intensity that can be maintained without considerable contribution of anaerobic metabolism.[27,30,50,72,115] Each higher intensity results in a clearly identifiable increase in bLa with time during constant load work.[50,86,88]

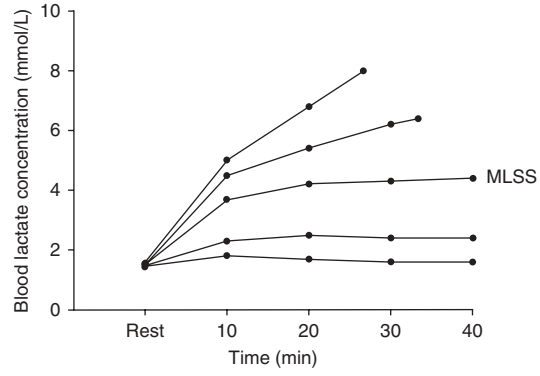

Fig. 2. The blood lactate response to several constant workload exercises with different intensities. The highest workload during which blood lactate concentrations can be still accepted as being steady state is defined as the maximal lactate steady state (MLSS).

The gold standard for the determination of the MLSS is performing several constant load trials of at least 30 minutes' duration on different days at various exercise intensities (in the range of 50–90% $\dot{V}O_{2max}$, figure 2).[49,50,86,116,117] An increase in bLa of not more than 1 mmol/L between 10 and 30 minutes during the constant load trials appears to be the most reasonable procedure for MLSS determination.[86,115]

MLSS represents a steady state in several but not all physiological parameters. For instance, oxygen uptake, carbon dioxide output, respiratory exchange ratio and bicarbonate concentration were reported to remain nearly constant during constant load exercise at MLSS, but respiratory rate and heart rate significantly increased during this time.[85,118]

In several endurance sports it is recommended to aim at a defined metabolic strain when a certain training stimulus is intended.[71,73,119,120] Therefore, it seems likely that training intensities for endurance training can be appropriately described when MLSS is known.

For the purposes of this review based on the above-mentioned rationales, LTs are considered valid as performance indicators when there are high linear correlations with (simulated) endurance performance. In addition, a close relationship between LTs and MLSS suggests validity with regard to the prescription of training intensities. Therefore, it is desirable that LTs should fulfil both validity criteria.

4. Lactate Threshold Concepts

For the purposes of the present paper, the MEDLINE database PubMed was searched for the search terms 'lactate threshold', 'aerobic threshold' and 'anaerobic threshold' combined with either 'endurance performance' or 'maximal lactate steady state'. Additionally, the references of the selected articles were searched for further relevant papers. The located original publications were searched for papers describing different LT concepts (section 4.1), a correlation between LTs and (simulated) endurance performance (section 4.2) or the relationship between LTs and the MLSS (section 4.3).

4.1 Located Lactate Threshold Concepts

A total of 25 different LT concepts were located. Two studies were excluded from the present analysis because threshold determination was not solely based on bLa but also took gas exchange measurements into account.[121,122] All threshold concepts were divided into three categories. Several authors used so-called fixed blood lactate thresholds (LT_{fix}) during incremental exercise to evaluate aerobic endurance performance. These fixed bLas were set at 2, 2.5, 3 or 4 mmol/L[24,108,123-125] with LT4 (4 mmol/L lactate threshold, originally described by Mader et al.[24] and by others later as the onset of blood lactate accumulation [OBLA][108]) being the most frequently used method.

4.1.1 Aerobic Lactate Thresholds

Table I shows an overview of LT concepts that could be categorized as the first rise in bLa above baseline levels (LT_{Aer}). Several researchers described the procedure to determine this threshold with terms like "the first significant/marked/systematic/non-linear/sharp/abrupt sustained increase in bLa above baseline".[30,110,126-133,138] Although the visual determination of the first rise of bLa above baseline levels seems obvious and simple, in practice it is associated with considerable problems because of the only slight changes in bLa on the first steps during GXTs. Yeh et al.[142] demonstrated that the visual detection of the LT_{Aer} (in that study called 'anaerobic threshold') led to relevant differences between observers. Therefore, it does not seem appropriate to determine this threshold by simple visual inspection. Thus, other methods were developed to make threshold determination more objective. For instance, some authors took the typical error of their lactate analysers into account and

Table I. Lactate threshold concepts that were categorized in the aerobic threshold category. For further explanation see text

Method and description
Work intensity or oxygen uptake
before/at which bLa begins to increase above baseline level[110,126]
at which bLa exhibits a marked/systematic/significant/non-linear/sharp/abrupt sustained increase above baseline value[30,110,127-133]
first significant elevation of lactate level (approximately 2 mmol/L)[30,34]
before an elevation in bLa above baseline (at least 0.2 mmol/L due to error of lactate analyser)[123,134]
rise in delta lactate (onset of plasma lactate accumulation)[109]
at minimum lactate equivalent (bLa divided by oxygen uptake or work intensity)[36,135-137]
at which plasma lactate concentration begins to increase when log bLa is plotted against log (work intensity)[53]
at which bLa increases 0.5 mmol/L above resting concentration[138]
at which bLa increases 1 mmol/L above baseline (i.e. lactate at low intensity corresponding to 40–60% $\dot{V}O_{2max}$)[111,139]
preceding a bLa increase by 1 mmol/L or more[140,141]

bLa = blood lactate concentrations; **$\dot{V}O_{2max}$** = maximal oxygen uptake.

Table II. Lactate threshold concepts that were categorized in the anaerobic threshold category. For further explanation see text

Threshold concept	Method and description
IAT (Stegmann et al.)[88]	Tangent to bLa curve from recovery curve where bLa is equal to the value at end of GXT
IAT (Keul et al.)[96]	Tangent to bLa curve at 51°
IAT (Simon et al.)[97]	Tangent to bLa curve at 45°
IAT (Berg et al.)[137]	Intersection point between tangent for the minimum lactate equivalent and the linear function for the final 90 sec of GXT
IAT (Bunc et al.)[143]	Intersection between the exponential regression of the lactate curve and the bisector of the tangents of the upper and lower parts of the lactate curve
IAT (Dickhuth et al.)[36,136]	1.5 mmol/L above minimum lactate equivalent
IAT (Baldari and Guidetti)[144]	The second lactate increase of at least 0.5 mmol/L from the previous value
D_{max} (Cheng et al.)[54]	Maximal distance from bLa curve to the line formed by its endpoints
D_{mod} (Bishop et al.)[140]	Maximal distance from bLa curve to the line formed by the point before the first rise in bLa and the value at cessation of exercise
Lactate turnpoint[103]	The final running velocity before the observation of a sudden and sustained increase in bLa between LT_{Aer} and $\dot{V}O_{2max}$
Lactate minimum speed[145]	Minimum in bLa during GXT after high intensity exercise

bLa = blood lactate concentration; **GXT** = incremental exercise test; **IAT** = individual anaerobic threshold; **LT_{Aer}** = aerobic threshold; **$\dot{V}O_{2max}$** = maximal oxygen uptake.

determined this LT as the workload 0.2 mmol/L above the lowest exercise lactate value.[123] Hughson and Green[138] arbitrarily chose an increase of 0.5 mmol/L above resting lactate concentrations. Another work group[111,139] chose a 1 mmol/L increment above lactate levels at low intensity (~40% to 60% $\dot{V}O_{2max}$) because it could be determined objectively and in a standardized manner in all subjects. Furthermore, the lowest value when bLa is divided by work intensity or $\dot{V}O_2$ has also been used as a marker for LT_{Aer} (minimum lactate equivalent).[36,135-137] Whereas Beaver and colleagues[53] used a log-log transformation to assess the first rise in bLa more objectively as the intersection of two linear regressions, Farrell et al.[109] plotted the difference in bLa between two consecutive stages against work intensity and determined the first rise of this relationship (onset of plasma lactate accumulation).

4.1.2 Anaerobic Lactate Thresholds

All threshold concepts that were assigned either to the MLSS or to a rapid/distinct change in the inclination of the blood lactate curve were categorized as LT_{An} (table II).

Originally, the LT4 was established because it seemed to be the highest bLa that was sustainable for a longer duration and, therefore, was regarded as the upper border for constant load endurance training.[24] It was soon recognized that a fixed bLa does not take into account considerable interindividual differences and that LT4 may frequently underestimate (particularly in anaerobically trained subjects) or overestimate (in aerobically trained athletes) real endurance capacity.[88,96,97,146] Therefore, several so-called 'individualized' LT concepts were developed. For instance, Keul et al.[96] and Simon et al.[97] determined the individual anaerobic threshold (IAT) at a certain inclination of the lactate curve (tangent of 51° and 45°, respectively). However, it seems questionable whether the use of a fixed inclination may reflect individual lactate kinetics better than a fixed bLa.

Stegmann et al.[88] developed a more complicated model that is based on the exercise lactate curve as well as on the lactate course during the early recovery period. This model is based on several assumptions regarding lactate distribution in blood and muscle compartments, lactate diffusion through biological membranes and lactate elimination. However, some of these premises have been challenged.[8,147]

Berg et al.[137] defined the LT_{An} as the intersection point between the tangent at the minimum lactate equivalent and the linear function

for the final 90 seconds of GXT. Similarly, Bunc et al.[143] determined the LT_{An} as the intersection between the exponential regression of the lactate curve and the bisector of the tangents on the upper and lower parts of the regression. A comparable model was established by Cheng et al.[54] and called the D_{max} method. Those authors determined the maximal perpendicular distance of the lactate curve from the line connecting the start with the endpoint of the lactate curve. It is obvious that these threshold models are dependent on the start intensity as well as the maximal effort spent by the subjects. To eliminate the influence of the start point of the GXT, Bishop et al.[140] connected the LT_{Aer} with the endpoint of the lactate curve and observed that this modified D_{max} threshold (D_{mod}) was also highly correlated with performance during a 1-hour time trial in 24 female cyclists.

Tegtbur et al.[145] developed the so-called lactate minimum test. This test starts with a short supramaximal exercise leading to high bLa. A short rest period (about 8 minutes)[145] should allow for an equilibrium between muscle and bLa. Immediately after this rest period, a standard incremental exercise test is conducted. After an initial fall of bLa at low exercise intensities, bLa begins to rise again. The lowest point of the lactate curve, the lactate minimum speed (LMS), is assumed to mark the LT_{An}. This procedure has recently been criticized because standardization is difficult.[112,148] For instance, the induced acidosis prior to the incremental test is unlikely to be uniform for different subjects. Additionally, initial intensity as well as stage increment and duration seem to affect LMS. Furthermore, supramaximal exercise might be contraindicated in some instances, for example in cardiac patients or in athletes at some time points during their training.

Baldari and Guidetti[144] defined the IAT as the workload corresponding to the second lactate increase of at least 0.5 mmol/L with the second increase greater than or equal to the first one. A limitation to this approach is that only discrete stages according to the test protocol can be identified as threshold workload. Additionally, those authors determined the IAT by plotting each lactate value against the preceding workload. This was claimed to be done because during 3-minute stages no steady-state lactate level could be reached[147] and, therefore, it was hypothesized that a lactate value at a given 3-minute stage would represent the realistic value of the previous stage.

From empirical observations, the work group of Dickhuth et al.[36,135,136] estimated the IAT at a blood lactate concentration 1.5 mmol/L above the minimum lactate equivalent (i.e. above LT_{Aer}). Finally, the lactate turnpoint (LTP) has been defined as the final running velocity before the observation of a sudden and sustained increase in bLa between LT_{Aer} and $\dot{V}O_{2max}$.[103]

Reproducibility of the velocity or power output at LTs has been reported to be high ($r > 0.9$, independent of whether LT_{fix}, LT_{Aer} or LT_{An} were analysed).[52,149-152] For $\dot{V}O_2$ at LTs, reliability coefficients seem to be slightly lower ($r = 0.8–0.9$).[150,152,153]

4.2 Lactate Thresholds and (Simulated) Competition Results

Thirty-eight studies were located that compared LT values with performance in endurance events or simulated competitions. Six studies were excluded from the analysis. Three of these studies compared an LT obtained during cycling exercise with running performance,[110,154,155] two studies only reported LT as a fraction of $\dot{V}O_{2max}$,[11,156] and one study reported correlations with time-to-exhaustion in an open-end interval programme.[157] A total of 32 studies were thus included in this analysis.

Eighteen studies evaluated the correlation of the work intensity (running velocity or $\dot{V}O_2$) at various LTs with performance in running competitions of different distances (800 m up to marathon; table III).[108,109,112,123,124,129-132,134,135,158-164] Competition distances from 0.8 to 3.2 km, from 5 km to 16.1 km and from 21.1 to 42.2 km were subsumed as correlates of short-, middle- and long-distance endurance events. The main result was that nearly all studies reported high correlation coefficients with (simulated) competition results. These results were confirmed by Weltman

Table III. Correlation coefficients between lactate thresholds and running performance over various distances

Threshold concept	0.8–3.2 km		5 km–16.1 km		19.3–42.2 km	
	v	$\dot{V}O_2$	v	$\dot{V}O_2$	v	$\dot{V}O_2$
LT_{fix}	0.82[135]	0.79[123]	0.88[135]	0.90[159]	0.91[135]	0.76[161]
	0.88[123]	0.75[123]	0.91[135]	0.92[159]	0.81[135]	0.83[163]
	0.86[123]	0.75[123]	0.91[159]	0.92[159]	0.98[124]	0.73[163]
	0.85[123]	0.72[134]	0.93[159]	0.83[159]	0.98[124]	
	0.87[134]	0.74[134]	0.91[159]	0.88[159]	0.98[124]	
	0.85[134]	0.75[134]	0.84[159]	0.93[159]	0.68[129]	
	0.84[134]	0.73[158]	0.91[159]	0.86[163]	0.96[108]	
	0.93[158]	0.60[132]	0.94[159]	0.74[163]	0.91[163]	
	0.78[132]	0.51[131]	0.83[160]		0.92[163]	
	0.68[131]	0.55[131]	0.81[112]			
	0.85[131]	0.69[131]	0.95[163]			
	0.88[131]		0.94[163]			
Median (min–max)	**0.85 (0.68–0.93)**	**0.73 (0.51–0.79)**	**0.91 (0.81–0.95)**	**0.89 (0.74–0.93)**	**0.92 (0.68–0.98)**	**0.76 (0.73–0.83)**
LT_{Aer}	0.74[135]	0.77[123]	0.73[135]	0.89[109]	0.76[135]	0.91[109]
	0.85[123]	0.61[134]	0.79[135]	0.91[109]	0.81[135]	0.89[109]
	0.70[134]	0.84[158]	0.78[160]	0.84[162]	0.78[129]	0.69[163]
	0.93[158]	0.69[132]	0.96[109]	0.83[162]	0.97[109]	0.52[163]
	0.77[132]	0.77[131]	0.97[109]	0.79[162]	0.98[109]	0.66[163]
	0.43[131]	0.66[131]	0.79[130]	0.69[162]	0.90[163]	0.42[163]
	0.65[131]	0.64[131]	0.83[130]	0.92[162]	0.91[163]	0.80[163]
	0.70[131]	0.85[109]	0.79[130]	0.79[162]	0.87[163]	0.65[163]
	0.91[109]	0.62[162]	0.84[130]	0.76[130]	0.86[163]	
		0.66[162]	0.83[130]	0.77[130]	0.83[163]	
		0.58[162]	0.81[130]	0.84[130]	0.77[163]	
			0.93[112]	0.81[130]		
			0.94[163]	0.82[130]		
			0.92[163]	0.88[130]		
			0.92[163]	0.72[163]		
			0.89[163]	0.56[163]		
			0.87[163]	0.66[163]		
			0.85[163]	0.52[163]		
				0.81[163]		
				0.69[163]		
Median (min–max)	**0.74 (0.43–0.93)**	**0.66 (0.58–0.85)**	**0.84 (0.73–0.97)**	**0.79 (0.45–0.92)**	**0.86 (0.76–0.98)**	**0.68 (0.42–0.91)**
LT_{An}	0.88[135]		0.91[135]	0.83[163]	0.93[135]	0.68[161]
			0.92[135]	0.70[163]	0.93[135]	0.83[163]
			0.86[160]	0.81[163]	0.90[163]	0.71[163]
			0.83[112]	0.66[163]	0.91[163]	0.81[163]
			0.93[163]	0.45[164]	0.90[163]	0.67[163]
			0.91[163]	0.45[164]	0.89[163]	
			0.94[163]			
			0.90[163]			
			0.76[164]			
			0.73[164]			
Median (min–max)	**0.88**		**0.91 (0.83–0.94)**	**0.76 (0.66–0.83)**	**0.91 (0.89–0.93)**	**0.71 (0.67–0.83)**

LT_{fix} = fixed lactate threshold; **LT_{Aer}** = aerobic threshold; **LT_{An}** = anaerobic threshold; **v** = velocity; **$\dot{V}O_2$** = oxygen uptake.

et al.,[123,134] who cross-validated the obtained regression equations and found high correlation coefficients between actual and predicted scores. There is a tendency for higher correlations with longer endurance events (0.43–0.93 in short-term events vs 0.68–0.98 over the long-distance competitions). Additionally, correlations tended to be higher for LT_{fix} and LT_{An} compared with LT_{Aer}. This might be due to the average intensity in running events being higher than the intensity

corresponding to the first increase in bLa. In total, the results of the analysed studies point to a common variance of LTs and competition results in running events between 55% and 85%.

In cycling, a total of eight studies evaluated the relationship between LTs and (simulated) cycling time trial performance (table IV).[12,89,140,141,165-168] Only one study analysed the correlation with short-duration time trial performance (4000 m individual pursuit) and found a high correlation coefficient of r = 0.86 in 18 male high-performance track cyclists.[167] Four studies evaluated distances between 13.5 and 20 km or time trial durations between 20 and 30 minutes.[89,165,166,168] The correlation coefficients in these studies were in most cases higher (between 0.8 and 0.9) than for the longer time trials (40 km or 60–90 minutes, r ~ 0.7).[140,141,165] Overall, the results of these studies were more heterogeneous. Correlation coefficients between LTs and (simulated) competition performance varied between r = 0.23[165] and r = 0.93.[89] In total, the results of the analysed studies point to a common variance of LTs and competition results between 35% and 85% in cycling events. However, the low number of studies and the heterogeneous results point to the need for further carefully designed studies to arrive at more comprehensive conclusions with regard to the relationship of LTs and time trial performance in cycling.

Two studies were found that analysed the relationship of LT markers with mountain bike cross-country race performance.[169,170] Such races are usually conducted on a graded terrain with considerable time spent ascending and descending. Impellizzeri et al.[170] observed high correlations between LT_{Aer} as well as OBLA and race time during a 31 km mountain bike race. Whereas correlations were about 0.7 when LT was expressed in absolute terms, correlations became considerably higher (~0.9) when power output at LT was expressed relative to body mass. Similarly, Gregory et al.[169] reported higher correlations between LT_{Aer} and a cross-country time trial in 11 male mountain bikers when LT_{Aer} was expressed as related to body mass (r ~ 0.5 in absolute terms vs r ~ 0.8 relative to body mass). This finding can be explained with the considerable influence of bodyweight and body composition on performance capacity in cyclists during ascents.[171-173]

In addition to the studies in running and cycling, another four studies were detected that evaluated LTs and (simulated) competition

Table IV. Correlation coefficients between lactate thresholds and cycling time trial events over various distances and times

Threshold concept	4 km		13.5–20 km; 20–30 min		40 km; 60–90 min	
	PO	$\dot{V}O_2$	PO	$\dot{V}O_2$	PO	$\dot{V}O_2$
LT_{fix}			0.23[165]		0.54[165]	
			0.82[166]		0.60[141]	
			0.90[166]		0.81[140]	
Median (min–max)			**0.82 (0.23–0.90)**		**0.60 (0.54–0.81)**	
LT_{Aer}	0.86[167]		0.67[165]		0.91[165]	0.93[12]
			0.88[166]		0.59[141]	
			0.86[166]		0.61[140]	
			0.91[168]		0.69[140]	
			0.88[168]		0.65[140]	
Median (min–max)	**0.86**		**0.88 (0.67–0.91)**		**0.65 (0.59–0.91)**	**0.93**
LT_{An}			0.45[165]		0.77[165]	
			0.89[166]		0.58[141]	
			0.91[166]		0.52[141]	
			0.93[89]		0.72[141]	
					0.84[140]	
					0.83[140]	
Median (min–max)			**0.90 (0.45–0.93)**		**0.75 (0.52–0.84)**	

LT_{Aer} = aerobic threshold; **LT_{An}** = anaerobic threshold; **LT_{fix}** = fixed lactate threshold; **PO** = power output; **$\dot{V}O_2$** = oxygen uptake.

performance. Two of these studies analysed competitive race walkers. Yoshida et al.[174] found correlation coefficients for OBLA as well as for LT_{Aer} of 0.94 and 0.85, respectively, with walking pace during a 5 km road race in eight female race walkers. Similar results were observed by Hagberg and Coyle[111] in a heterogeneous group of race walkers with correlation coefficients of 0.94 and 0.82 for velocity and oxygen uptake at LT_{Aer} in a 20 km race walking performance.

Two studies dealt with rowing performance and LTs. Whereas Ingham et al.[175] observed high correlations (r = 0.86–0.92) between work rate at fixed and aerobic LTs and 2000 m ergometer performance in 41 rowers of different categories, Cosgrove et al.[176] found considerably lower correlations (r = 0.39–0.73) in 13 male rowers.

To summarize, the overwhelming majority of published studies on the relationship between LTs and endurance performance showed strong correlations, particularly for running events. This supports findings of earlier training studies that found training-induced improvements in competitive performance significantly correlated with improvements in LTs.[130,162] Although it seems likely that other influences such as central nervous system processes may have regulatory and decisive characteristics in endurance events as it was recently claimed,[177] peripheral metabolic adaptations highly related to the LT[46] seem to be a necessary and important prerequisite for aerobic endurance performance.

4.3 Lactate Thresholds and Maximal Lactate Steady State

MLSS determination has become very popular in performance diagnosis in several endurance sports. Thus, numerous studies have dealt with the problem of an adequate estimation of MLSS during one single laboratory visit. For instance, some authors tried to estimate MLSS from performance during all-out time trials (5 km or 40 km)[114,178] from physiological strain (bLa, heart rate, ratings of perceived exertion) during standardized sub-maximal constant-load exercise[179-182] or from gas exchange measurements.[183-189] However, an overview of those studies is beyond the scope of the present review.

There are several studies that examined the metabolic responses during steady-state exercise intensities related to LTs but did not analyse exercise intensities slightly above or below. Schnabel et al.[190] observed average steady-state lactate concentrations (~4.5 mmol/L) during 50-minute runs at the IAT according to Stegmann et al.[88] However, no other intensity was analysed in this investigation. Stegmann and Kindermann[146] compared 50-minute cycling exercise in 19 subjects at the IAT as well as at LT4 and found steady-state lactate levels (~4 mmol/L) during IAT trials, whereas exercise at LT4 resulted in continuously rising bLa (up to 9.6 mmol/L) and a premature cessation. This is in line with findings of Oyono-Enguelle et al.,[191] who similarly reported no lactate steady state in three out of five subjects during exercise at LT4. In contrast, Loat and Rhodes[189] found continuously increasing bLa (on average from 3.4 mmol/L after 15 minutes to 4.6 mmol/L after 45 minutes) and premature fatigue during 60-minute constant load trials at the IAT. However, those authors did not use the originally described test protocol and Heck[50] has shown that IAT determination is dependent on the protocol used.

Baldari and Guidetti[144] compared steady-state running at their IAT determined when lactate values were plotted against the corresponding exercise intensity (IAT_m) and against the preceding intensity (IAT_a) and found steady-state lactate levels for IAT_a (~4 mmol/L^{-1}) but not for IAT_m. However, due to the determination procedure, the difference between both thresholds was exactly one stage increment and no other intensities in between were evaluated. Ribeiro et al.[192] assessed a 40-minute steady-state cycling exercise at LT_{Aer}, between LT_{Aer} and LT_{An} (LTP), at LT_{An} as well as between LT_{An} and maximum. Those authors found on average steady-state lactate levels up to LT_{An} (~5 mmol/L^{-1}), whereas at the highest intensity, bLa increased continuously and exercise had to be terminated prematurely.

Bacon and Kern[193] and Tegtbur et al.[145] compared constant load trials at LMS and 5% or 0.2 m/s, respectively, above the LMS. Those

authors found that LMS intensity but not the higher intensity on average resulted in a lactate steady state. However, in the study of Bacon and Kern,[193] the average blood lactate increase between minutes 12 and 28 during the constant load trial at the LMS +5% intensity was 1.2 mmol/L, and in four out of ten subjects a lactate steady state according to the recommended criterion[72,115] was present.

A total of 11 studies evaluated the relationship between one or more LT concepts and MLSS using the recommended procedure, including several constant load trials of at least 30 minutes' duration to determine the MLSS (table V). One study determined MLSS with 20-minute constant load trials.[113]

Most researchers analysed the relationship of LT4 with MLSS.[49,72,90,92,112,117] For instance, Heck and colleagues[49,50,72] found strong correlations between LT4 and MLSS during running as well as during cycling exercise. However, the fitness level of their subjects was quite heterogeneous and, therefore, the high correlations to some extent might be spurious. Additionally, they observed that the velocity at LT4 was higher than MLSS velocity when stage duration during the GXT was 3 minutes, whereas this was not the case with 5-minute stages. Therefore, these authors concluded that LT4 gives a valuable estimate of the MLSS when stage duration is at least 5 minutes. Also, Jones and Doust[112] found a high correlation between LT4 and the MLSS in a homogenous group of trained runners with LT4 being higher than MLSS (3-minute stages). Lower correlations were found by van Schuylenbergh et al.[92] in elite cyclists as well as by Beneke[117] in a homogenous group of rowers. Also, LT4 and MLSS did not differ significantly with 6-minute stages,[92] whereas LT4 was considerably higher than MLSS with 3-minute stages.[117] Lajoie et al.[90] evaluated whether the intensity corresponding to 4 mmol/L lactate during a GXT with 8-minute stages and 30 W increments is appropriate to estimate the MLSS in nine cyclists. Average power output at MLSS and LT4 was not significantly different. However, because bLa at MLSS differed considerably between subjects, the authors concluded that it is unrealistic to rely on a blood lactate value of 4 mmol/L as a universal criterion for MLSS. Unfortunately, a more detailed analysis regarding the correlation or individual differences between LT4 and MLSS was not reported.

Heck et al.[49,50] observed high correlations between MLSS and the IAT according to Stegmann et al.[88] In addition, running velocity was not significantly different between IAT and MLSS independent of stage duration (3 or 5 minutes), whereas in cycling IAT was about 8% higher than MLSS. Urhausen et al.[86] found in runners as well as in cyclists that constant load trials at IAT resulted on average in a lactate steady state, whereas a 5% higher intensity led to a continuous rise in bLa. Similarly, McLellan and Jacobs[91] arrived at the conclusion that the IAT is a valid estimate for the MLSS in most subjects, although there exists a considerable difference in a few cases. Unfortunately, these studies reported no measure of correlation between IAT and MLSS or no quantitative data on individual differences between IAT and MLSS. In contrast to the previously mentioned studies, Beneke[117] found the IAT to be considerably higher than MLSS in nine rowers. Additionally, the correlation in this study was lower than was observed by Heck et al.[49] This finding might be due to the more homogenous performance level of the rowers as well as to the slow increment in the chosen test protocol.[50]

Heck et al.[49] and Heck[50] found high correlations between the IAT according to Keul et al.[96] and Bunc et al.[143] and the MLSS in running and cycling. However, the high correlations might be partly accounted for by the heterogenous endurance level of the subjects. Furthermore, both thresholds were dependent on the test protocol during the running tests (3-minute vs 5-minute stages).

The LMS was evaluated in two studies.[89,112] The results of these studies were contradictory. Jones and Doust[112] found only a low correlation between LMS and MLSS. Additionally, LMS was considerably lower than MLSS. In contrast, LMS was not significantly different from MLSS in the study of MacIntosh et al.[89] These contrasting observations might have been due to

Table V. Comparison of lactate threshold concepts with MLSS determined by several constant load trials of different intensity

Threshold concept	Subjects	Main outcome	Reference
LT4, OBLA	16 healthy males (running)	High correlation between LT4 and MLSS (r = 0.98) LT4 on average 0.12 m/s higher than MLSS with 3 min stages but not with 5 min stages during GXT Heterogenous endurance level	Heck et al.[49,72]
	22 healthy subjects (cycling)	Significant correlation between LT4 and MLSS (r = 0.92) LT4 on average 19.9 W higher than MLSS Heterogenous endurance level, slow increase in power output (+6 W/min)	Heck[50]
	8 trained male runners	High correlation (r = 0.93) between OBLA and MLSS OBLA on average 0.4 km/h higher than MLSS	Jones and Doust[112]
	21 elite cyclists	Low correlation (r = 0.71) between LT4 and MLSS No significant difference between LT4 and MLSS (MLSS 15 W higher) Homogenous endurance level	Van Schuylenbergh et al.[92]
	9 male rowers	Significant correlation (r = 0.82) between LT4 and MLSS LT4 significantly higher (32 W) than MLSS Homogenous endurance level	Beneke[117]
	10 well trained cyclists	Average power output at LT4 and MLSS was not significantly different (282 W vs 277 W) Strong MLSS criterion (<0.75 mmol/L from 10–60 min) No further data on correlations or intraindividual differences between LT4 and MLSS	Lajoie et al.[90]
IAT (Stegmann et al.[88])	16 healthy males (running)	High correlation between IAT and MLSS (r = 0.96–0.98) IAT velocity on average similar to MLSS for 3 min as well as 5 min stages during GXT Heterogenous endurance level of subjects	Heck et al.[49]
	22 healthy subjects (cycling)	Significant correlation between IAT and MLSS (r = 0.87) IAT on average 15.1 W higher than MLSS Heterogenous endurance level, slow increase in power output (+6 W/min) not corresponding to the originally described test protocol	Heck[50]
	16 trained cyclists 14 trained runners	CLT at and below IAT resulted on average in LSS but not CLT at 105% IAT 100% IAT does not in all individuals exactly represent MLSS LSS was found in 6 (of 14 runners) and 9 (of 16 cyclists) at 105% IAT No further data on correlations or intraindividual differences between IAT and MLSS CLT at LT4 (cycling at 104% IAT) resulted on average not in a LSS	Urhausen et al.[86]
	11 males (cycling)	No LSS during CLT at IAT +5% $\dot{V}O_{2max}$; only 1 LSS during CLT at IAT +2.5% $\dot{V}O_{2max}$ Two subjects showed no LSS during CLT at IAT −7.5% $\dot{V}O_{2max}$, all other subjects showed LSS during CLT at IAT −2.5% $\dot{V}O_{2max}$ No further data on correlations or intraindividual differences between IAT and MLSS	McLellan and Jacobs[91]
	9 male rowers	Significant correlation (r = 0.81) between IAT and MLSS IAT significantly higher (32 W) than MLSS	Beneke[117]
IAT (Keul et al.[96])	16 healthy males (running)	High correlation between IAT and MLSS (r = 0.98) IAT velocity on average 0.2 m/s higher than MLSS with 3 min stages and slightly lower with 5 min stages during GXT Heterogenous endurance level of subjects	Heck et al.[49]
	22 healthy subjects (cycling)	Significant correlation between IAT and MLSS (r = 0.94) IAT on average 21.0 W higher than MLSS Heterogenous endurance level, slow increase in power output (+6 W/min^{-1})	Heck[50]

Continued next page

Table V. Contd

Threshold concept	Subjects	Main outcome	Reference
IAT (Bunc et al.[143])	16 healthy males (running)	High correlation between IAT and MLSS (r = 0.98–0.99) IAT velocity on average considerably higher than MLSS for 3-min (+0.31 m/s) as well as 5 min stages (+0.14 m/s) during GXT Heterogenous endurance level of subjects	Heck et al.[49]
	22 healthy subjects (cycling)	Significant correlation between IAT and MLSS (r = 0.89) IAT on average 71.5 W higher than MLSS Heterogenous endurance level, slow increase in power output (+6 W/min)	Heck[50]
LMS	10 trained male runners	Low correlation (r = 0.61) between LMS and MLSS LMS on average 0.8 km/h lower than MLSS	Jones and Doust[112]
	14 cyclists or triathletes	LMS on average not different from MLSS No good estimate of MLSS by LMS in three subjects MLSS criterion: <0.7 mmol/L during last 20 min No further data on correlations or intraindividual differences between LMS and MLSS	MacIntosh et al.[89]
D_{mod}	21 elite cyclists	Significant correlation (r = 0.85) between D_{mod} threshold and MLSS D_{mod} threshold significantly lower (–23 W) than MLSS	Van Schuylenbergh et al.[92]
LTP	8 males (running)	No correlation between LTP and MLSS (r = 0.18) On average no difference between LTP and MLSS (13.7 vs 13.8 km/h) 95% LoA[194] = ±1.8 km/h	Smith and Jones[103]
LT_{Aer}	10 trained male runners	High correlation (r = 0.94) between LT_{Aer} and MLSS LT_{Aer} on average 0.6 km/h lower than MLSS	Jones and Doust[112]
	11 male recreational runners	No correlation of LT_{Aer} with MLSS (speed: r = –0.01; $\dot{V}O_2$: r = –0.47) LT_{Aer} on average 1.1 km/h lower than MLSS 20 min CLT, but strong MLSS criterion (<0.2 mmol/L)	Haverty et al.[113]

CLT = constant load trial; **D_{mod}** = maximal distance from blood lactate concentration (bLa) curve to the line formed by the point before the first rise in bLa and the value at cessation of exercise; **GXT** = incremental exercise test; **IAT** = individual anaerobic threshold; **LMS** = lactate minimum speed; **LoA** = limits of agreement; **LSS** = lactate steady state; **LT4** = 4 mmol/L lactate threshold; **LT_{Aer}** = aerobic threshold; **LTP** = lactate turnpoint; **MLSS** = maximal lactate steady state; **OBLA** = onset of blood lactate accumulation; **r** = correlation coefficient; **$\dot{V}O_{2max}$** = maximal oxygen uptake.

the considerably different test protocols used in both studies. This is in line with the findings of Carter et al.[148] showing that LMS is highly dependent on the test protocol.

For other threshold concepts, scientific data regarding the relationship of the threshold and MLSS are scarce. Van Schuylenbergh et al.[92] found a significant correlation between the D_{mod}-threshold and MLSS, although D_{mod} was significantly lower than MLSS. In contrast, LTP was found to be not different from MLSS on average, but it was not correlated to MLSS and the 95% limits of agreement (LoA)[194] of the difference between LTP and MLSS were wide.[103]

There were also two studies that analysed the relationship between MLSS and LT_{Aer}.[112,113] As could be expected, LT_{Aer} was situated considerably below the MLSS in both studies. Whereas Jones and Doust[112] reported a high correlation between LT_{Aer} and MLSS, Haverty et al.[113] did not. This might be due to short constant load trials (20 minutes) and the strict MLSS criterion (<0.2 mmol/L increase during the last 10 minutes) in the latter study, which does not sufficiently consider the time course of bLa changes and may have led to an underestimation of the real MLSS.[115]

To summarize, there is evidence that some LT concepts might be able to estimate the MLSS. In particular, the IAT according to Stegmann et al.,[88] and LT4 were repeatedly examined. Mostly linear regressions or average lactate courses were reported. Correlations and regressions determine relative reliability of two methods but do not assess systematic bias or absolute agreement. Furthermore, they depend greatly on the range of values in the analysed sample.[195] Thus, from a practical and statistical point of

Table VI. Mean bias (difference maximal lactate steady state [MLSS]-LT) and 95% limits of agreement (LoA) for four different lactate threshold concepts during treadmill (n = 16) and cycle ergometry (n = 22). Results calculated from raw data reported by Heck et al.[49,50,72] (with permission)

Lactate threshold concept	Treadmill ergometry 3 min stages, +0.4 m/s			Treadmill ergometry 5 min stages, +0.4 m/s			Cycle ergometry 2 min stages, +25 W		
	mean bias (m/s)	LoA (m/s)	LoA (%)	mean bias (m/s)	LoA (m/s)	LoA (%)	mean bias (W)	LoA (W)	LoA (%)
LT4	−0.13	±0.35	±8	0.02	±0.39	±9	−19.8	±28.4	±14
IAT (Keul et al.[96])	−0.20	±0.39	±9	0.06	±0.35	±8	−21.0	±22.4	±11
IAT (Stegmann et al.[88])	−0.03	±0.51	±12	−0.03	±0.37	±9	−15.0	±35.0	±18
IAT (Bunc et al.[143])	−0.33	±0.33	±8	−0.14	±0.37	±9	−71.4	±52.8	±27

IAT = individual anaerobic threshold; **LT4** = 4 mmol/L threshold.

view it would be of interest to know the absolute variability of individual differences between the LT and MLSS. An appropriate means to report this variability may be the mean bias and the 95% LoA as it was described by Bland and Altman.[194] There is only one study available that applied this procedure.[103] Such a procedure would also allow for assessing heteroscedasticity (i.e. whether the differences depend on the magnitude of the mean or – in this case – endurance capacity).[195]

Table VI shows an example calculation of the mean bias and the 95% LoA for four different LT concepts from raw data reported by Heck et al.[49,50,72] These data show a mean bias between 0.5% and 8%, with LoA of about 10% in a running exercise. This means that for each new subject within the study population it could be expected (with a 95% probability) that the difference between MLSS and the respective LT is within these LoA.[195] For the cycling exercise the results are more heterogenous with greater mean bias and LoA. However, due to the limited data points these observations are preliminary and should be confirmed by further research.

5. Conclusions and Perspectives

In conclusion, it can be stated that a huge amount of evidence exists that LT concepts are of considerable importance for the diagnosis as well as the prediction of aerobic endurance performance. The concept of the aerobic-anaerobic transition may serve as a reasonable means for performance diagnosis and intensity prescription in endurance sports. However, there are several open questions that should be appropriately addressed by future research. These are:

- Whereas the relationship of LTs with competition performance is well established in running events and less strongly in cycling, there is lack of evidence for most other endurance sports.
- Scientific studies comparing LTs with MLSS are rare and the results are partially conflicting. This might be due to different methodological approaches. It is suggested that the MLSS be assessed by the established procedure using several constant load trials with different intensities[72,115] and that the MLSS be compared with a chosen LT. To do so, measures of absolute agreement between LTs and MLSS should be reported according to the method introduced by Bland and Altman.[194]
- In this context, it is important to know the basic variability and reproducibility of the MLSS. Up to now, no scientific data addressing this question exist. Therefore, it is recommended to evaluate the variability of MLSS in future research. Of note, this may enable an evaluation of the differences between LT and MLSS compared with the basic variability of the MLSS and, thus, give more detailed information on the quality of the MLSS estimate.

Although there has been much and controversial debate on the LT phenomenon during the last three decades, many scientific studies have dealt with LT concepts, their value in as-

sessing endurance performance or in prescribing exercise intensities in endurance training. It might be speculated that a considerable part of the debate has to be attributed to the misinterpretation of the physiological basis of the phenomenon. The presented framework may help to clarify the controversy and may give a rational basis for performance diagnosis and training prescriptions in future research as well as in sports practice.

Acknowledgements

No sources of funding were used to assist in the preparation of this review. The authors have no conflicts of interest that are relevant to the content of this manuscript.

References

1. Gladden LB. Lactate metabolism: a new paradigm for the third millennium. J Physiol 2004 Jul 1; 558 (Pt 1): 5-30
2. Fletcher WM, Hopkins FG. Lactic acid in amphibian muscle. J Physiol (London) 1907; 35: 247-309
3. Meyerhof O. Untersuchung über die Wärmeströmung der vitalen Oxydationsvorgänge. Biochem Z 1911; 5: 246-328
4. Douglas CG, Haldane JS. The regulation of normal breathing. J Physiol 1909; 38: 420-40
5. Ryffel GH. Lactic acid metabolism: a critical review. Quart J Med 1910; 3: 221-3
6. Hill AV, Lupton H. Muscular exercise, lactic acid and the supply and utilization of oxygen. Quart J Med 1923; 16: 135-71
7. Margaria R, Edwards HT, Dill DB. The possible mechanism of contracting and paying the oxygen debt and the role of lactic acid in muscular contraction. Am J Physiol 1933; 106: 689-714
8. Gladden LB. Muscle as a consumer of lactate. Med Sci Sports Exerc 2000 Apr; 32 (4): 764-71
9. Brooks GA. The lactate shuttle during exercise and recovery. Med Sci Sports Exerc 1986 Jun; 18 (3): 360-8
10. Robergs RA, Ghiasvand F, Parker D. Biochemistry of exercise-induced metabolic acidosis. Am J Physiol Regul Integr Comp Physiol 2004 Sep; 287 (3): R502-16
11. Coyle EF, Coggan AR, Hopper MK, et al. Determinants of endurance in well-trained cyclists. J Appl Physiol 1988; 64 (6): 2622-30
12. Coyle EF, Feltner ME, Kautz SA, et al. Physiological and biomechanical factors associated with elite endurance cycling performance. Med Sci Sports Exerc 1991 Jan; 23 (1): 93-107
13. Lucía A, Pardo J, Durántez A, et al. Physiological differences between professional and elite road cyclists. Int J Sports Med 1998; 19: 342-8
14. Impellizzeri FM, Marcora SM, Rampinini E, et al. Correlations between physiological variables and performance in high level cross-country off-road cyclists. Br J Sports Med 2005 Oct; 39 (10): 747-51
15. Sjodin B, Svedenhag J. Applied physiology of marathon running. Sports Med 1985 Mar-Apr; 2 (2): 83-99
16. Faria EW, Parker DL, Faria IE. The science of cycling: physiology and training, part 1. Sports Med 2005; 35 (4): 285-312
17. Jacobs I. Blood lactate: implications for training and sports performance. Sports Med 1986; 3 (1): 10-25
18. Conley DL, Krahenbuhl GS. Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc 1980; 12 (5): 357-60
19. Hollmann W. 42 years ago: development of the concepts of ventilatory and lactate threshold. Sports Med 2001; 31 (5): 315-20
20. Meyer T, Scharhag J, Kindermann W. Peak oxygen uptake: myth and truth about an internationally accepted reference value. Z Kardiol 2005 Apr; 94 (4): 255-64
21. Hollmann W. Höchst- und dauerleistungsfähigkeit des sportlers. München: Barth, 1963
22. Wasserman K, McIlroy MB. Detecting the threshold of anaerobic metabolism in cardiac patients. Am J Cardiol 1964; 14: 844-52
23. Wells JG, Balke B, Van Fossan DD. Lactic acid accumulation during work: a suggested standardization of work classification. J Appl Physiol 1957 Jan; 10 (1): 51-55
24. Mader A, Liesen H, Heck H, et al. Zur Beurteilung der sportartspezifischen ausdauerleistungsfähigkeit im labor. Sportarzt Sportmed 1976; 27: 80-8, 109-12
25. Atkinson G, Davison R, Jeukendrup A, et al. Science and cycling: current knowledge and future directions for research. J Sports Sci 2003 Sep; 21 (9): 767-87
26. Jones AM. The physiology of the world record holder for the womeńs marathon. Int J Sports Sci Coaching 2006; 1 (2): 101-16
27. Svedahl K, MacIntosh BR. Anaerobic threshold: the concept and methods of measurement. Can J Appl Physiol 2003 Apr; 28 (2): 299-323
28. Brooks GA. Anaerobic threshold: review of the concept and directions for future research. Med Sci Sports Exerc 1985; 17 (1): 22-34
29. Myers J, Ashley E. Dangerous curves: a perspective on exercise, lactate, and the anaerobic threshold. Chest 1997 Mar; 111 (3): 787-95
30. Kindermann W, Simon G, Keul J. The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training. Eur J Appl Physiol 1979; 42: 25-34
31. Meyer T, Lucia A, Earnest CP, et al. A conceptual framework for performance diagnosis and training prescription from submaximal gas exchange parameters: theory and application. Int J Sports Med 2005 Feb; 26 Suppl. 1: S38-48
32. McLellan TM, Skinner JS. The use of the aerobic threshold as a basis for training. Can J Appl Sport Sci 1981; 6 (4): 197-201
33. McLellan TM. The anaerobic threshold: concept and controversy. Austr J Sci Med Sport 1987; 19 (2): 3-8
34. Skinner JS, McLellan TH. The transition from aerobic to anaerobic metabolism. Res Q Exerc Sport 1980; 51 (1): 234-48

35. Wasserman K, Whipp BJ, Koyl SN, et al. Anaerobic threshold and respiratory gas exchange during exercise. J Appl Physiol 1973; 35 (2): 236-43
36. Dickhuth HH, Yin L, Niess A, et al. Ventilatory, lactate-derived and catecholamine thresholds during incremental treadmill running: relationship and reproducibility. Int J Sports Med 1999 Feb; 20 (2): 122-7
37. Peronnet F, Aguilaniu B. Lactic acid buffering, nonmetabolic CO2 and exercise hyperventilation: a critical reappraisal. Respir Physiol Neurobiol 2006 Jan 25; 150 (1): 4-18
38. Yoshida T, Udo M, Chida M, et al. Specificity of physiological adaptation to endurance training in distance runners and competitive walkers. Eur J Appl Physiol Occup Physiol 1990; 61 (3-4): 197-201
39. Acevedo EO, Goldfarb AH. Increased training intensity effects on plasma lactate, ventilatory threshold, and endurance. Med Sci Sports Exerc 1989; 21 (5): 563-8
40. Bosquet L, Leger L, Legros P. Methods to determine aerobic endurance. Sports Med 2002; 32 (11): 675-700
41. Mujika I, Padilla S. Cardiorespiratory and metabolic characteristics of detraining in humans. Med Sci Sports Exerc 2001 Mar; 33 (3): 413-21
42. McLellan TM, Gass GC. The relationship between the ventilation and lactate thresholds following normal, low and high carbohydrate diets. Eur J Appl Physiol Occup Physiol 1989; 58 (6): 568-76
43. Reilly T, Woodbridge V. Effects of moderate dietary manipulations on swim performance and on blood lactate-swimming velocity curves. Int J Sports Med 1999 Feb; 20 (2): 93-7
44. Yoshida T. Effect of dietary modifications on lactate threshold and onset of blood lactate accumulation during incremental exercise. Eur J Appl Physiol 1984; 53 (3): 200-5
45. Maassen N, Busse MW. The relationship between lactic acid and work load: a measure for endurance capacity or an indicator of carbohydrate deficiency? Eur J Appl Physiol Occup Physiol 1989; 58 (7): 728-37
46. Midgley AW, McNaughton LR, Jones AM. Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? Sports Med 2007; 37 (10): 857-80
47. Bentley DJ, Newell J, Bishop D. Incremental exercise test design and analysis: implications for performance diagnostics in endurance athletes. Sports Med 2007; 37 (7): 575-86
48. Foxdal P, Sjodin B, Sjodin 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
49. Heck H, Hess G, Mader A. Comparative study of different lactate threshold concepts [Vergleichende Untersuchung zu verschiedenen Laktat-Schwellenkonzepten]. Dtsch Z Sportmed 1985; 36 (1+2): 19-25, 40-52
50. Heck H. Laktat in der Leistungsdiagnostik. Schorndorf: Hofmann, 1991
51. Lundberg MA, Hughson RL, Weisiger KH, et al. Computerized estimation of lactate threshold. Comput Biomed Res 1986 Oct; 19 (5): 481-6
52. Grant S, McMillan K, Newell J, et al. Reproducibility of the blood lactate threshold, 4 mmol.l(-1) marker, heart rate and ratings of perceived exertion during incremental treadmill exercise in humans. Eur J Appl Physiol 2002 Jun; 87 (2): 159-66
53. Beaver WL, Wasserman K, Whipp BJ. Improved detection of lactate threshold during exercise using a log-log transformation. J Appl Physiol 1985; 59 (6): 1936-40
54. Cheng B, Kuipers H, Snyder AC, et al. A new approach for the determination of ventilatory and lactate thresholds. Int J Sports Med 1992; 13 (7): 518-22
55. Hughson RL, Weisiger KH, Swanson GD. Blood lactate concentration increases as a continuous function in progressive exercise. J Appl Physiol 1987; 62 (5): 1975-81
56. Robergs RA, Chwalbinska-Moneta J, Mitchell JB, et al. Blood lactate threshold differences between arterialized and venous blood. Int J Sports Med 1990; 11 (6): 446-51
57. Feliu J, Ventura JL, Segura R, et al. Differences between lactate concentration of samples from ear lobe and the finger tip. J Physiol Biochem 1999 Dec; 55 (4): 333-9
58. McNaughton LR, Thompson D, Philips G, et al. A comparison of the lactate Pro, Accusport, Analox GM7 and Kodak Ektachem lactate analysers in normal, hot and humid conditions. Int J Sports Med 2002 Feb; 23 (2): 130-5
59. Thin AG, Hamzah Z, FitzGerald MX, et al. Lactate determination in exercise testing using an electrochemical analyser: with or without blood lysis? Eur J Appl Physiol Occup Physiol 1999 Jan; 79 (2): 155-9
60. Buono MJ, Yeager JE. Intraerythrocyte and plasma lactate concentrations during exercise in humans. Eur J Appl Physiol Occup Physiol 1986; 55 (3): 326-9
61. Forsyth JJ, Farrally MR. A comparison of lactate concentration in plasma collected from the toe, ear, and fingertip after a simulated rowing exercise. Br J Sports Med 2000 Feb; 34 (1): 35-8
62. Draper N, Brent S, Hale B, et al. The influence of sampling site and assay method on lactate concentration in response to rock climbing. Eur J Appl Physiol 2006 Nov; 98 (4): 363-72
63. Hildebrand A, Lormes W, Emmert J, et al. Lactate concentration in plasma and red blood cells during incremental exercise. Int J Sports Med 2000 Oct; 21 (7): 463-8
64. Foxdal P, Sjodin B, Rudstam H, et al. Lactate concentration differences in plasma, whole blood, capillary finger blood and erythrocytes during submaximal graded exercise in humans. Eur J Appl Physiol Occup Physiol 1990; 61 (3-4): 218-22
65. Foxdal P, Sjodin A, Ostman B, et al. The effect of different blood sampling sites and analyses on the relationship between exercise intensity and 4.0 mmol.l-1 blood lactate concentration. Eur J Appl Physiol Occup Physiol 1991; 63 (1): 52-4
66. Medbø JI, Mamen A, Holt Olsen O, et al. Examination of four different instruments for measuring blood lactate concentration. Scand J Clin Lab Invest 2000 Aug; 60 (5): 367-80
67. Buckley JD, Bourdon PC, Woolford SM. Effect of measuring blood lactate concentrations using different auto-

mated lactate analysers on blood lactate transition thresholds. J Sci Med Sport 2003 Dec; 6 (4): 408-21

68. van Someren KA, Howatson G, Nunan D, et al. Comparison of the Lactate Pro and Analox GM7 blood lactate analysers. Int J Sports Med 2005 Oct; 26 (8): 657-61
69. Bishop D. Evaluation of the Accusport lactate analyser. Int J Sports Med 2001 Oct; 22 (7): 525-30
70. Lucía A, Hoyos J, Chicarro JL. Physiology of professional road cycling. Sports Med 2001; 31 (5): 325-37
71. Weltman A. The blood lactate response to exercise. Champaign IL: Human Kinetics, 1995
72. Heck H, Mader A, Hess G, et al. Justification of the 4-mmol/l lactate threshold. Int J Sports Med 1985; 6 (3): 117-30
73. Seiler KS, Kjerland GO. Quantifying training intensity distribution in elite endurance athletes: is there evidence for an ''optimal'' distribution? Scand J Med Sci Sports 2006 Feb; 16 (1): 49-56
74. Esteve-Lanao J, San Juan AF, Earnest CP, et al. How do endurance runners actually train? Relationship with competition performance. Med Sci Sports Exerc 2005 Mar; 37 (3): 496-504
75. Bourdon P. Blood lactate transition thresholds: concepts and controversies. In: Gore J, editor. Physiological tests for elite athletes/Australian Sports Commission. Champaign (IL): Human Kinetics, 2000: 50-65
76. Meyer T, Faude O, Urhausen A, et al. Different effects of two regeneration regimens on immunological parameters in cyclists. Med Sci Sports Exerc 2004 Oct; 36 (10): 1743-9
77. Meyer T, Gorge G, Schwaab B, et al. An alternative approach for exercise prescription and efficacy testing in patients with chronic heart failure: a randomized controlled training study. Am Heart J 2005 May; 149 (5): e1-7
78. McConnell TR, Clark BA, Conlin NC, et al. Gas exchange anaerobic threshold: implications for prescribing exercise in cardiac rehabilitation. J Cardiopulmonary Rehabil 1993; 13: 31-6
79. Faude O, Meyer T, Urhausen A, et al. Recovery training in cyclists: ergometric, hormonal and psychometric findings. Scand J Med Sci Sports. Epub 2008 Apr 23
80. Weltman A, Seip RL, Snead D, et al. Exercise training at and above the lactate threshold in previously untrained women. Int J Sports Med 1992; 13 (3): 257-63
81. Londeree BR. Effect of training on lactate/ventilatory thresholds: a meta-analysis. Med Sci Sports Exerc 1997 Jun; 29 (6): 837-43
82. Scharhag J, Meyer T, Gabriel HH, et al. Does prolonged cycling of moderate intensity affect immune cell function? Br J Sports Med 2005 Mar; 39 (3): 171-7
83. Meyer T, Gabriel HH, Auracher M, et al. Metabolic profile of 4 h cycling in the field with varying amounts of carbohydrate supply. Eur J Appl Physiol 2003 Jan; 88 (4-5): 431-7
84. Meyer T, Faude O, Gabriel H, et al. Ventilatory threshold and individual anaerobic threshold are reliable prescriptors for intensity of cycling training [abstract]. Med Sci Sports Exerc 2000; 32 Suppl. 5: S171
85. Baron B, Noakes TD, Dekerle J, et al. Why does exercise terminate at the maximal lactate steady state intensity? Br J Sports Med 2008 Oct; 42 (10): 528-33
86. Urhausen A, Coen B, Weiler B, et al. Individual anaerobic threshold and maximum lactate steady state. Int J Sports Med 1993; 14 (3): 134-9
87. Mader A, Heck H. A theory of the metabolic origin of ''anaerobic threshold''. Int J Sports Med 1986 Jun; 7 Suppl. 1: 45-65
88. Stegmann H, Kindermann W, Schnabel A. Lactate kinetics and individual anaerobic threshold. Int J Sports Med 1981; 2: 160-5
89. MacIntosh BR, Esau S, Svedahl K. The lactate minimum test for cycling: estimation of the maximal lactate steady state. Can J Appl Physiol 2002 Jun; 27 (3): 232-49
90. Lajoie C, Laurencelle L, Trudeau F. Physiological responses to cycling for 60 minutes at maximal lactate steady state. Can J Appl Physiol 2000 Aug; 25 (4): 250-61
91. McLellan TM, Jacobs I. Reliability reproducibility and validity of the individual anaerobic threshold. Eur J Appl Physiol 1993; 67 (2): 125-31
92. 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 Aug; 25 (6): 403-8
93. Beneke R, Hutler M, Leithauser RM. Maximal lactate-steady-state independent of performance. Med Sci Sports Exerc 2000 Jun; 32 (6): 1135-9
94. Beneke R, von Duvillard SP. Determination of maximal lactate steady state response in selected sports events. Med Sci Sports Exerc 1996 Feb; 28 (2): 241-6
95. Beneke R, Leithauser RM, Hutler M. Dependence of the maximal lactate steady state on the motor pattern of exercise. Br J Sports Med 2001 Jun; 35 (3): 192-6
96. Keul J, Simon G, Berg A, et al. Bestimmung der individuellen anaeroben Schwelle zur Leistungsbewertung und Trainingsgestaltung. Dtsch Z Sportmed 1979; 30: 212-8
97. 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
98. Coen B. Individuelle anaerobe Schwelle-Methodik und Anwendung in der sportmedizinischen Leistungsdiagnostik und Trainingssteuerung leichtathletischer Laufdisziplinen. Köln: Sport und Buch Strauss, 1997
99. Coen B, Schwarz L, Urhausen A, et al. Control of training in middle- and long-distance running by means of the individual anaerobic threshold. Int J Sports Med 1991; 12 (6): 519-24
100. Niess AM, Fehrenbach E, Strobel G, et al. Evaluation of stress responses to interval training at low and moderate altitudes. Med Sci Sports Exerc 2003 Feb; 35 (2): 263-9
101. Niess AM, Röcker K, Baumann I, et al. Laktatverhalten bei extensiven Tempolaufbelastungen unter Flachland- und moderaten Höhenbedingungen. Leistungssport 1999; (3): 49-53
102. Faude O, Meyer T, Scharhag J, et al. Volume vs intensity in the training of competitive swimmers. Int J Sports Med 2008 Nov; 29 (11): 906-12
103. Smith CG, Jones AM. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. Eur J Appl Physiol 2001 Jul; 85 (1-2): 19-26

104. Davis HA, Bassett J, Hughes P, et al. Anaerobic threshold and lactate turnpoint. Eur J Appl Physiol 1983; 50 (3): 383-92

105. Urhausen A, Weiler B, Coen B, et al. Plasma catecholamines during endurance exercise of different intensities as related to the individual anaerobic threshold. Eur J Appl Physiol 1994; 69: 16-20

106. Gabriel H, Kindermann W. The acute immune response to exercise: what does it mean? Int J Sports Med 1997; 18 Suppl. 1: S28-45

107. Lucia A, Sanchez O, Carvajal A, et al. Analysis of the aerobic-anaerobic transition in elite cyclists during incremental exercise with the use of electromyography. Br J Sports Med 1999 Jun; 33 (3): 178-85

108. Sjodin B, Jacobs I. Onset of blood lactate accumulation and marathon running performance. Int J Sports Med 1981; 2 (1): 23-6

109. Farrell PA, Wilmore JH, Coyle EF, et al. Plasma lactate accumulation and distance running performance. Med Sci Sports 1979; 11 (4): 338-44

110. Yoshida T, Chida M, Ichioka M, et al. Blood lactate parameters related to aerobic capacity and endurance performance. Eur J Appl Physiol 1987; 56 (1): 7-11

111. Hagberg JM, Coyle EF. Physiological determinants of endurance performance as studied in competitive racewalkers. Med Sci Sports Exerc 1983; 15: 287-9

112. Jones AM, Doust JH. The validity of the lactate minimum test for determination of the maximal lactate steady state. Med Sci Sports Exerc 1998 Aug; 30 (8): 1304-13

113. Haverty M, Kenney WL, Hodgson JL. Lactate and gas exchange responses to incremental and steady state running. Br J Sports Med 1988; 22 (2): 51-4

114. Harnish CR, Swensen TC, Pate RR. Methods for estimating the maximal lactate steady state in trained cyclists. Med Sci Sports Exerc 2001 Jun; 33 (6): 1052-5

115. Beneke R. Methodological aspects of maximal lactate steady state: implications for performance testing. Eur J Appl Physiol 2003 Mar; 89 (1): 95-9

116. Billat VL, Sirvent P, Py G, et al. The concept of maximal lactate steady state: a bridge between biochemistry, physiology and sport science. Sports Med 2003; 33 (6): 407-26

117. Beneke R. Anaerobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing. Med Sci Sports Exerc 1995; 27 (6): 863-7

118. Baron B, Dekerle J, Robin S, et al. Maximal lactate steady state does not correspond to a complete physiological steady state. Int J Sports Med 2003 Nov; 24 (8): 582-7

119. Urhausen A, Coen B, Kindermann W. Individual assessment of the aerobic-anaerobic transition by measurements of blood lactate. In: Garrett Jr WE, Kirkendall DT, editors. Exercise and sport science. Philadelphia (PA): Lippincott Williams & Wilkins, 2000: 267-75

120. Mujika I, Busso T, Geyssant A, et al. Modeling the effects of training in competitive swimming. In: Troup JP, Hollander AP, Strasse D, editors. Biomechanics and medicine in swimming. London: E & FN Spon, 1996: 221-8

121. Kumagai S, Tanaka K, Matsuura Y, et al. Relationships of the anaerobic threshold with the 5 km, 10 km, and 10 mile races. Eur J Appl Physiol 1982; 49 (1): 13-23

122. Aunola S, Rusko H. Does anaerobic threshold correlate with maximal lactate steady-state? J Sports Sci 1992; 10 (4): 309-23

123. Weltman A, Snead D, Seip R, et al. Prediction of lactate threshold and fixed blood lactate concentrations from 3200-m running performance in male runners. Int J Sports Med 1987 Dec; 8 (6): 401-6

124. Föhrenbach R, Mader A, Hollmann W. Determination of endurance capacity and prediction of exercise intensities for training and competition in marathon runners. Int J Sports Med 1987; 8: 11-8

125. Hurley BF, Hagberg JM, Allen WK, et al. Effect of training on blood lactate levels during submaximal exercise. J Appl Physiol 1984; 56 (5): 1260-4

126. Ivy JL, Withers RT, Van Handel PJ, et al. Muscle respiratory capacity and fiber type as determinants of the lactate threshold. J Appl Physiol 1980 Mar; 48 (3): 523-7

127. Caiozzo VJ, Davis JA, Ellis JF, et al. A comparison of gas exchange indices used to detect the anaerobic threshold. J Appl Physiol 1982; 53 (5): 1184-9

128. Tanaka H. Predicting running velocity at blood lactate threshold from running performance tests in adolescent boys. Eur J Appl Physiol 1986; 55 (4): 344-8

129. Tanaka K, Matsuura Y. Marathon performance, anaerobic threshold, and onset of blood lactate accumulation. J Appl Physiol 1984; 57 (3): 640-3

130. Tanaka K, Matsuura Y, Matsuzaka A, et al. A longitudinal assessment of anaerobic threshold and distance-running performance. Med Sci Sports Exerc 1984 Jun; 16 (3): 278-82

131. Yoshida T, Udo M, Iwai K, et al. Significance of the contribution of aerobic and anaerobic components to several distance running performances in female athletes. Eur J Appl Physiol Occup Physiol 1990; 60 (4): 249-53

132. Yoshida T, Udo M, Iwai K, et al. Physiological characteristics related to endurance running performance in female distance runners. J Sports Sci 1993 Feb; 11 (1): 57-62

133. Davis JA, Vodak P, Wilmore JH, et al. Anaerobic threshold and maximal aerobic power for three modes of exercise. J Appl Physiol 1976 Oct; 41 (4): 544-50

134. Weltman J, Seip R, Levine S, et al. Prediction of lactate threshold and fixed blood lactate concentrations from 3200-m time trial running performance in untrained females. Int J Sports Med 1989 Jun; 10 (3): 207-11

135. Roecker K, Schotte O, Niess AM, et al. Predicting competition performance in long-distance running by means of a treadmill test. Med Sci Sports Exerc 1998 Oct; 30 (10): 1552-7

136. Dickhuth HH, Huonker M, Münzel T, et al. Individual anaerobic threshold for evaluation of competitive athletes and patients with left ventricular dysfunctions. In: Bachl N, Graham TE, Löllgen H, editors. Advances in ergometry. Berlin: Springer, 1991: 173-9

137. Berg A, Stippig J, Keul J, et al. Zur Beurteilung der Leistungsfähigkeit und Belastbarkeit von Patienten mit coronarer Herzkrankheit. Dtsch Z Sportmed 1980; 31: 199-205

138. Hughson RL, Green HJ. Blood acid-base and lactate relationships studied by ramp work tests. Med Sci Sports Exerc 1982; 14 (4): 297-302

139. Coyle EF, Martin WH, Ehsani AA, et al. Blood lactate threshold in some well-trained ischemic heart disease patients. J Appl Physiol 1983 Jan; 54 (1): 18-23
140. Bishop D, Jenkins DG, Mackinnon LT. The relationship between plasma lactate parameters, W_{peak} and 1-h cycling performance in women. Med Sci Sports Exerc 1998 Aug; 30 (8): 1270-5
141. Amann M, Subudhi AW, Foster C. Predictive validity of ventilatory and lactate thresholds for cycling time trial performance. Scand J Med Sci Sports 2006 Feb; 16 (1): 27-34
142. Yeh MP, Gardner RM, Adams TD, et al. ''Anaerobic threshold'': problems of determination and validation. J Appl Physiol 1983 Oct; 55 (4): 1178-86
143. Bunc V, Heller J, Novack J, et al. Determination of the individual anaerobic threshold. Acta Univ Carol, Gymnica 1985; 27: 73-81
144. Baldari C, Guidetti L. A simple method for individual anaerobic threshold as predictor of max lactate steady state. Med Sci Sports Exerc 2000 Oct; 32 (10): 1798-802
145. Tegtbur U, Busse MW, Braumann KM. Estimation of an individual equilibrium between lactate production and catabolism during exercise. Med Sci Sports Exerc 1993 May; 25 (5): 620-7
146. Stegmann H, Kindermann W. Comparison of prolonged exercise tests at the individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol/l lactate. Int J Sports Med 1982; 3 (2): 105-10
147. Orok CJ, Hughson RL, Green HJ, et al. Blood lactate responses in incremental exercise as predictors of constant load performance. Eur J Appl Physiol 1989; 59 (4): 262-7
148. Carter H, Jones AM, Doust JH. Effect of incremental test protocol on the lactate minimum speed. Med Sci Sports Exerc 1999 Jun; 31 (6): 837-45
149. Coen B, Urhausen A, Kindermann W. Individual anaerobic threshold: methodological aspects of its assessment in running. Int J Sports Med 2001 Jan; 22 (1): 8-16
150. Weltman A, Snead D, Stein P, et al. Reliability and validity of a continuous incremental treadmill protocol for the determination of lactate threshold, fixed blood lactate concentrations, and $\dot{V}O_{2max}$. Int J Sports Med 1990; 11 (1): 26-32
151. Aunola S, Rusko H. Reproducibility of aerobic and anaerobic thresholds in 20-50 year old men. Eur J Appl Physiol 1984; 53 (3): 260-6
152. Pfitzinger P, Freedson PS. The reliability of lactate measurements during exercise. Int J Sports Med 1998 Jul; 19 (5): 349-57
153. Zhou S, Weston SB. Reliability of using the D-max method to define physiological responses to incremental exercise testing. Physiol Meas 1997 May; 18 (2): 145-54
154. Takeshima N, Tanaka K. Prediction of endurance running performance for middle-aged and older runners. Br J Sports Med 1995 Mar; 29 (1): 20-3
155. Tanaka K, Matsuura Y, Kumagai S, et al. Relationships of anaerobic threshold and onset of blood lactate accumulation with endurance performance. Eur J Appl Physiol Occup Physiol 1983; 52 (1): 51-6
156. Bourdin M, Messonnier L, Hager JP, et al. Peak power output predicts rowing ergometer performance in elite male rowers. Int J Sports Med 2004 Jul; 25 (5): 368-73
157. Bjorklund G, Pettersson S, Schagatay E. Performance predicting factors in prolonged exhausting exercise of varying intensity. Eur J Appl Physiol 2007 Mar; 99 (4): 423-9
158. Grant S, Craig I, Wilson J, et al. The relationship between 3 km running performance and selected physiological variables. J Sports Sci 1997 Aug; 15 (4): 403-10
159. Fay L, Londeree BR, LaFontaine TP, et al. Physiological parameters related to distance running performance in female athletes. Med Sci Sports Exerc 1989 Jun; 21 (3): 319-24
160. Nicholson RM, Sleivert GG. Indices of lactate threshold and their relationship with 10-km running velocity. Med Sci Sports Exerc 2001 Feb; 33 (2): 339-42
161. Lehmann M, Berg A, Kapp R, et al. Correlations between laboratory testing and distance running performance in marathoners of similar performance ability. Int J Sports Med 1983 Nov; 4 (4): 226-30
162. Tanaka K, Watanabe H, Konishi Y, et al. Longitudinal associations between anaerobic threshold and distance running performance. Eur J Appl Physiol Occup Physiol 1986; 55 (3): 248-52
163. Tokmakidis SP, Leger LA, Pilianidis TC. Failure to obtain a unique threshold on the blood lactate concentration curve during exercise. Eur J Appl Physiol Occup Physiol 1998 Mar; 77 (4): 333-42
164. Stratton E, O'Brien BJ, Harvey J, et al. Treadmill velocity best predicts 5000-m run performance. Int J Sports Med 2009; 30 (1): 40-5
165. Bentley DJ, McNaughton LR, Thompson D, et al. Peak power output, the lactate threshold, and time trial performance in cyclists. Med Sci Sports Exerc 2001 Dec; 33 (12): 2077-81
166. McNaughton LR, Roberts S, Bentley DJ. The relationship among peak power output, lactate threshold, and short-distance cycling performance: effects of incremental exercise test design. J Strength Cond Res 2006 Feb; 20 (1): 157-61
167. Craig NP, Norton KI, Bourdon PC, et al. Aerobic and anaerobic indices contributing to track endurance cycling performance. Eur J Appl Physiol Occup Physiol 1993; 67 (2): 150-8
168. Nichols JF, Phares SL, Buono MJ. Relationship between blood lactate response to exercise and endurance performance in competitive female master cyclists. Int J Sports Med 1997 Aug; 18 (6): 458-63
169. Gregory J, Johns DP, Walls JT. Relative versus absolute physiological measures as predictors of mountain bike cross-country race performance. J Strength Cond Res 2007 Feb; 21 (1): 17-22
170. Impellizzeri FM, Rampinini E, Sassi A, et al. Physiological correlates to off-road cycling performance. J Sports Sci 2005 Jan; 23 (1): 41-47
171. Coyle EF. Improved muscular efficiency displayed as Tour de France champion matures. J Appl Physiol 2005 Jun; 98 (6): 2191-6

172. Lucia A, Earnest C, Arribas C. The Tour de France: a physiological review. Scand J Med Sci Sports 2003 Oct; 13 (5): 275-83
173. Impellizzeri FM, Marcora SM. The physiology of mountain biking. Sports Med 2007; 37 (1): 59-71
174. Yoshida T, Udo M, Iwai K, et al. Physiological determinants of race walking performance in female race walkers. Br J Sports Med 1989 Dec; 23 (4): 250-4
175. Ingham SA, Whyte GP, Jones K, et al. Determinants of 2000 m rowing ergometer performance in elite rowers. Eur J Appl Physiol 2002 Dec; 88 (3): 243-6
176. Cosgrove MJ, Wilson J, Watt D, et al. The relationship between selected physiological variables of rowers and rowing performance as determined by a 2000 m ergometer test. J Sports Sci 1999 Nov; 17 (11): 845-52
177. Noakes TD. The central governor model of exercise regulation applied to the marathon. Sports Med 2007; 37 (4-5): 374-7
178. Swensen TC, Harnish CR, Beitman L, et al. Noninvasive estimation of the maximal lactate steady state in trained cyclists. Med Sci Sports Exerc 1999 May; 31 (5): 742-6
179. Snyder AC, Woulfe T, Welsh R, et al. A simplified approach to estimating the maximal lactate steady state. Int J Sports Med 1994; 15 (1): 27-31
180. Kilding AE, Jones AM. Validity of a single-visit protocol to estimate the maximum lactate steady state. Med Sci Sports Exerc 2005 Oct; 37 (10): 1734-40
181. Billat V, Dalmay F, Antonini MT, et al. A method for determining the maximal steady state of blood lactate concentration from two levels of submaximal exercise. Eur J Appl Physiol Occup Physiol 1994; 69 (3): 196-202
182. Palmer AS, Potteiger JA, Nau KL, et al. A 1-day maximal lactate steady-state assessment protocol for trained runners. Med Sci Sports Exerc 1999 Sep; 31 (9): 1336-41
183. Loat CE, Rhodes EC. Relationship between the lactate and ventilatory thresholds during prolonged exercise. Sports Med 1993; 15 (2): 104-15
184. Simon J, Young JL, Gutin B, et al. Lactate accumulation relative to the anaerobic and respiratory compensation thresholds. J Appl Physiol 1983; 54 (1): 13-7
185. Yamamoto Y, Miyashita M, Hughson RL, et al. The ventilatory threshold gives maximal lactate steady state. Eur J Appl Physiol 1991; 63 (1): 55-9
186. Scheen A, Juchmes J, Cession-Fossion A. Critical analysis of the "anaerobic threshold" during exercise at constant workloads. Eur J Appl Physiol Occup Physiol 1981; 46 (4): 367-77
187. Laplaud D, Guinot M, Favre-Juvin A, et al. Maximal lactate steady state determination with a single incremental test exercise. Eur J Appl Physiol 2006 Mar; 96 (4): 446-52
188. Dekerle J, Baron B, Dupont L, et al. Maximal lactate steady state, respiratory compensation threshold and critical power. Eur J Appl Physiol 2003 May; 89 (3-4): 281-8
189. Loat CER, Rhodes EC. Comparison of the lactate and ventilatory thresholds during prolonged work. Biol Sport 1996; 13 (1): 3-12
190. Schnabel A, Kindermann W, Schmitt WM, et al. Hormonal and metabolic consequences of prolonged running at the individual anaerobic threshold. Int J Sports Med 1982; 3 (3): 163-8
191. Oyono-Enguelle S, Heitz A, Marbach J, et al. Blood lactate during constant-load exercise at aerobic and anaerobic thresholds. Eur J Appl Physiol 1990; 60 (5): 321-30
192. Ribeiro JP, Hughes V, Fielding RA, et al. Metabolic and ventilatory responses to steady state exercise relative to lactate thresholds. Eur J Appl Physiol Occup Physiol 1986; 55 (2): 215-21
193. Bacon L, Kern M. Evaluating a test protocol for predicting maximum lactate steady state. J Sports Med Phys Fitness 1999 Dec; 39 (4): 300-8
194. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986 Feb 8; 1 (8476): 307-10
195. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med 1998 Oct; 26 (4): 217-38

Correspondence: Dr *Oliver Faude*, Institute of Sports and Preventive Medicine, University of Saarland, Campus Bldg. B 8.2, 66123 Saarbrücken, Germany.
E-mail: o.faude@mx.uni-saarland.de