The Lactate Minimum Test for Cycling: Estimation of the Maximal Lactate Steady State

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Catalog Data

Key Words: anaerobic threshold, endurance, blood lactate
Mots clés: seuil anaérobie, endurance, lactate sanguin

Abstract/Résumé

This study evaluated the reliability and validity of the lactate minimum test (LMT), an incremental test given after lactic acidosis was induced by sprint exercise. This test is purported to accurately estimate the intensity of exercise at which the transport of lactate into and out of the blood is in equilibrium (maximal lactate steady state or MLSS) and should be a good predictor of endurance performance. Fourteen athletes (mean age 27.2 ± 3.7 yrs) completed the following on Kreitler rollers: (a) two 20-km time-trials (35.1 ± 3.3 and 35.7 ± 3.5 km·hr⁻¹, p < .05); (b) two LMTs yielding lactate minimum speeds (LMS) of 33.6 ± 3.4 and 33.4 ± 3.1 km·hr⁻¹ (p > .06); and (c) four constant intensity rides, at speeds bracketing the LMS. At 33.5 ± 3.1 km·hr⁻¹ plasma lactate concentration decreased 0.4 ± 1.6 mM from 10 to 30 min. Plasma lactate increased 1.6 ± 0.7 mM while riding 0.9 ± 0.9 km·hr⁻¹ faster. The LMT is a reliable ($r^2 = 0.904$) and valid method to predict MLSS and a good predictor of endurance performance (LMT vs. 20-km time-trial, $r^2 = 0.86$).

Cette étude analyse la fiabilité et la validité du test du minimum de lactate (LMT), un test progressif administré à la suite d’une acidose lactique obtenue par un exercice de sprint. Ce test est conçu pour estimer avec précision l’intensité d’exercice qui indique le niveau d’équilibre entre le lactate entrant et celui sortant du circuit vasculaire (régime stable du maximum de lactate ou MLSS) ; ce test devrait donc être un bon indicateur de la performance d’endurance. Quatorze athlètes (27,2 ± 3,7 ans) font les exercices suivants sur des...
rouleaux de marque Kreitler: (a) deux essais contre la montre sur une distance de 20 km
(35,1 ± 3,3 et 35,7 ± 3,5 km · h⁻¹, p < 0,05); (b) deux LMT révélant les vitesses en présence
d'un minimum de lactate (LMS): 33,6 ± 3,4 et 33,4 ± 3,1 km · h⁻¹ (p > 0,6); et (c) quatre
séances d'intensité constante selon un régime correspondant au LMS. À une vitesse de 33,5
± 3,1 km · h⁻¹ la concentration de lactate diminue de 0,4 ± 1,6 mM de la 10e à la 30e min. En
augmentant la vitesse de 0,9 ± 0,9 km · h⁻¹, la concentration plasmatique de lactate augmente
de 1,6 ± 0,7 mM. Le LMT est fiable (r² = 0,904) et mesure bien de façon indirecte le MLSS ;
il est aussi un bon prédicteur de la performance d'endurance (LMT vs 20 km contre la
montre, r² = 0,86).

Introduction

For many years researchers have attempted to discriminate between endurance
athletes in a given sport, using physiological measures (MacDougall et al., 1991).
Parameters such as maximal oxygen uptake (Nemoto et al., 1988), ventilatory
thresholds (Bune et al., 1987; Costill et al., 1973; Fohrenbach et al., 1987; Kumagi
et al., 1982; Lehmann et al., 1983; Péronnet et al., 1987), and lactate thresholds
measured in various ways (Farrell et al., 1979; Jacobs, 1986; Sjodin et al., 1981,
1982; Sjodin and Svedenhag, 1985; Svedenhag and Sjodin, 1984; Weltman et al.,
1987) have been used. More recently, the maximal lactate steady state (MLSS) has
been suggested as a discriminator in endurance performance capability (Snyder et
al., 1994).

Maximal lactate steady state is defined as the highest intensity of exercise
that can be sustained while maintaining a constant blood lactate concentration
(Tegtbuer et al., 1993). Thus, this measure should be a defining characteristic in
events lasting from 30 to 60 min, such as a 10 to 20-km running race or a 20 to 40-
km cycling time-trial. To confirm that MLSS has been attained (or more specifically,
exceeded), it is necessary to perform constant intensity exercise for at least
30 min, with blood samples obtained during and at the end of this exercise. MLSS
has been identified as the highest intensity for which blood lactate does not in-
crease during the final 20 min of the test (Carter et al., 1999; Heck et al., 1985;
Jones and Doust, 1998; Palmer et al., 1999; Swensen et al., 1999). The actual
speed at MLSS cannot be identified. In practice, a speed just greater than MLSS is
identified by an increase in lactate concentration, usually by a fixed amount (0.5 to
1 mM) during the final 20 min of a 30-min test. The speed just slower than this
one, and for which lactate concentration did not increase by the criterion amount,
is considered to be the apparent MLSS speed. Obviously, the true MLSS probably
lies between these two identified speeds, and the precision of the estimate depends
on the magnitude of the increments between the tested speeds being particularly small.

Tegtbuer et al. (1993) developed the lactate minimum test (LMT) in order to
estimate the MLSS, based on the work of Davis and Gass (1979). This method has
a sound theoretical basis (Davis and Gass, 1979) and has been validated for run-
ning on a track (Tegtbuer et al., 1993). However, the test has not been universally
accepted, as researchers in some laboratories (Carter et al., 1999; Jones and Doust,
1998) have been unable to consistently obtain valid estimates of MLSS from the
LMT.

The LMT is an incremental exercise test that is initiated under conditions of
high blood lactate concentration. The athlete first performs two brief, high intensity
bouts of exercise to elevate blood lactate. This is followed by a rest period in order to permit equilibration of muscle and blood lactate, and then an incremental exercise test is done. While exercising below the MLSS, the rate of removal of lactate from the blood will exceed the rate of addition of lactate to the blood from active muscles. As the intensity of exercise increases, there will be an intensity at which the rate of lactate accumulation exceeds the rate of removal, and blood lactate concentration will increase. Curve-fitting provides a mathematical expression of the relationship between blood lactate concentration and intensity (speed) of exercise. The speed associated with the blood lactate minimum in this curve is defined as the lactate minimum speed (LMS). This speed should represent the intensity of exercise at which the movement of lactate into and out of the blood is in equilibrium, which has been shown to be equivalent to the MLSS of an individual for running (Tegtbur et al., 1993). It seems appropriate to adapt the test to other endurance events, like cycling.

The MLSS is an important parameter to measure for three reasons. The first is that it appears to be a more specific discriminator of endurance performance between athletes with similar maximal oxygen uptake values (Coyle et al., 1988). Secondly, and most importantly, the MLSS can be used to assess training status. It would be expected that MLSS should increase if the training regimen adopted by the athlete is effective. Thirdly, MLSS can be used in training program design, and as an educational tool for athletes. Endurance programs could be divided into three training zones: low intensity, near MLSS, and an intensity in excess of MLSS.

The purpose of this investigation was to determine the reliability and validity of the LMT as a predictor of the MLSS for cycling. As well, this measure was evaluated as a predictor of cycling endurance performance.

Methods

SUBJECTS

Fourteen male and female cyclists or triathletes participated in this study, which was approved by a University of Calgary research ethics committee. All participants completed a Physical Activity Readiness Questionnaire (Thomas et al., 1992) and gave written informed consent. Each subject was asked to abstain from training or strenuous exercise for at least 24 hr prior to each test. The subject group was heterogeneous in terms of cycling experience and ability, including recreational and elite athletes.

OVERVIEW

Prior to the study, the subjects had participated in a minimum of 8 weeks of regular endurance training. It was anticipated that this criterion would minimize variability due to training-induced changes during this study, since several testing sessions were required. Subjects continued their regular training programs throughout the study, incorporating the testing sessions into their programs. Prior to exercise testing; height, weight and skinfold measurements were obtained. This was done primarily to inform the subjects of their body composition (7-site; Jackson and Pollock, 1977) and to provide a measure of the physical characteristics of these subjects. A series of exercise tests were completed in the following order:
20-km time-trial, two LMTs, four constant speed rides and a final 20-km time-trial. The procedures and rationale for each of these tests are presented below.

KREITLER ROLLERS

Each subject rode their own racing (road) bicycle on Kreitler rollers (Kreitler Rollers Inc., Ottawa, KS) with the “Killer Headwind” resistance device set to simulate road conditions, according to the manufacturer’s specifications. The front forks were supported in a steel stand. Rear tire pressure was identical for each of the testing sessions for a given subject. The Kreitler rollers were instrumented for continuous measurement of velocity of the roller under the rear wheel, with a device similar to that used to measure flywheel velocity (MacIntosh and MacEachern, 1997). Subjects were provided continuous feedback of their current speed and distance covered using a standard cyclocomputer, which was calibrated to the rear wheel of the bicycle. Cadence was not controlled in this study. Subjects could select their own gearing and were permitted to change gears during the course of the test.

TWENTY KILOMETER TIME-TRIAL

Subjects were asked to complete a 20-km time-trial in the least amount of time possible on the Kreitler rollers. Participants were constantly informed of the speed and distance covered. Heart rate was measured by a Polar Vantage XL heart rate monitor (Polar Inc., Woodbury, NY) and recorded at five km intervals. Speed was continuously measured throughout the trial. The purpose of this time-trial was to provide an estimate of a starting speed for the incremental portion of the LMT, to assess the ability level of the subjects, and to determine the relationship between the time-trial and the LMS. There should be a high correlation between these measures if the LMS is a good predictor of endurance performance. The speed for the first stage of the incremental test was 4 km · hr⁻¹ slower than the average speed during the time-trial. This speed was chosen as the starting speed, because it was anticipated that the LMS would be close to the time-trial speed. Although the inclusion of the 20-km time-trial lengthened the protocol beyond one testing session, it was considered to be a worthy time investment. Having an estimation of starting speed permits more precise estimation of the LMS by allowing for smaller increment steps. Also, considering that the test would be administered repeatedly with a given athlete (i.e., monitoring their training program) it seems unlikely that it would be necessary to repeat the 20-km time-trial each time the LMT was administered.

LACTATE MINIMUM TESTS

The lactate minimum test used in this study was patterned after the one described by Tegtbur et al. (1993). Lactic acidosis was induced by two successive sprint rides of 500 m with an intervening 60-s recovery period. It was essential that these efforts resulted in a relatively high blood lactate level, yet did not fatigue the subjects to the point that the incremental test could not be completed. A post-effort blood lactate concentration of 8 mM has been recommended in the literature (Carter et al., 1999). The subjects were instructed to treat the 500 m as a time trial, but all-
out effort was not required. The sprints were followed by an 8-min recovery, during which time slow, easy riding was permitted.

After the rest period, subjects completed an incremental test to exhaustion, consisting of rides starting four km · hr⁻¹ slower than the average speed from the 20-km time-trial, with one km · hr⁻¹ increments and 1 min of rest between stages. The distance cycled in each stage was 1500 m in order to permit measurable blood lactate exchange. It has previously been shown that 400 m running stages (lasting approximately 1.4 to 2 min) were not of sufficient duration to permit accurate estimation of the LMS (Tegtbier et al., 1993). Pacing was provided using visual feedback of speed. The actual speed during these trials was monitored with an encoder affixed to one of the rollers, and data were collected by a computer.

Finger tip blood samples (50 µl) were obtained between the 7th and 8th min of the recovery period and during the rest intervals of the incremental test. The average heart rate over the last 30 s of each stage was recorded. The LMS was determined by fitting the plasma lactate vs. speed data to a second order polynomial function, using Microsoft Excel, (Microsoft Corp. Richmond, WA). The heart rate response during the incremental test was consistently linear with respect to speed, and linear regression was used to predict the heart rate corresponding to the LMS. This was done to compare the heart rate predicted to occur at the LMS with the heart rate during the constant speed trials. The LMT was repeated within 7 days using identical procedures (LMT1 and LMT2). This second test was used to evaluate the reproducibility of the measure of LMS.

CONSTANT SPEED RIDES

To allow the determination of MLSS, four 30-min constant speed rides were completed on separate days. These rides were done with target velocities below (minus one km · hr⁻¹), at, and above (plus one and plus two km · hr⁻¹) the LMS. In each case, subjects were permitted a 10- to 15-min warm up. Total distance was recorded, and average speed was calculated from the computer collected roller velocity. Heart rate, distance, and finger-tip blood samples (50 µl) for plasma lactate analysis were obtained after 10 min of the ride, and every 5 min thereafter, until 30 min had elapsed or the subject was unable to maintain the required intensity. A 0.7 mM increase in plasma lactate from 10 min to 30 min during the constant speed ride was selected as the criterion that the intensity was above the MLSS. This criterion represents a compromise between the 0.2 mM increase (Haverty et al., 1988) and the 1.0 mM increase (Carter et al., 1999; Heck et al., 1985; Jones and Doust, 1998; Palmer et al., 1999) commonly reported in the literature.

20-KM TIME-TRIAL #2

After the participants had completed the above testing, they were asked to do another 20-km time-trial as short a time as possible on the Kreitler rollers. The purpose of this trial was to determine if there was any learning or training effects over the duration of these tests. The final time-trial might better relate to the LMS if the initial 20-km time-trial was not a good effort, due to unfamiliarity with the testing equipment and effort required. Alternatively, since the study required several tests, over the course of two to four weeks, there was the possibility of a training or detraining effect. This second time-trial permitted evaluation of this
possibility.

LACTATE CONCENTRATION ANALYSIS

Blood samples were collected in capillary tubes, pretreated with potassium oxalate and sodium fluoride. These samples were centrifuged (1500 g for 10 min) and lactate concentration was measured in 10 μL of plasma using the Sigma lactate kit (Sigma Diagnostics, St. Louis, MO). Absorbance was measured at 540 nm wavelength with a Beckman DU-62 Spectrophotometer (Beckman Instruments Inc., Fullerton, CA).

STATISTICS

Standard statistical procedures were used (Microsoft Excel): linear regression, nonlinear regression, correlation, paired t-tests and descriptive statistics (means and standard deviations). A Bland and Altman test (Bland and Altman, 1986) was used to evaluate reproducibility of the LMT. Analysis of variance was done with Statistica (Statsoft, Tulsa, OK). All results are presented as mean ± SD; \( p < 0.05 \) was considered significant.

Results

PHYSICAL CHARACTERISTICS AND TIME-TRIALS

The physical characteristics of the subjects who participated in this study are presented in Table 1. The average speed maintained in time-trial 1 was 34.8 ± 3.2 km \cdot hr\(^{-1}\) (mean ± SD). The speed of the second time-trial was 35.3 ± 3.4 km \cdot hr\(^{-1}\) and this was significantly faster than the first (\( p < 0.05 \)). The range of speeds observed in time-trial one was 28.9 to 38.8 km-hr\(^{-1}\), and in time-trial two 27.7 to 39.6 km \cdot hr\(^{-1}\). Although the difference was significant, it was equivalent to only 1.6% (mean change = 0.6 ± 1.0 km \cdot hr\(^{-1}\)). Only two subjects' speed changed by more than 1.5 km \cdot hr\(^{-1}\) (or 4.3% on average), indicating a high level of reproducibility (\( r^2 = 0.89 \)) in this test, with a modest learning or training effect over the time-course of the study. A linear relationship (see Figure 1) was apparent between the first LMT and the best 20 km time-trial: 20- km time-trial speed = 0.907 LMS + 5.09, with \( r^2 = 0.914 \).

<table>
<thead>
<tr>
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<th>Body fat(^a)</th>
<th>Age (years)</th>
<th>Body mass (kg)</th>
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<tbody>
<tr>
<td>Males (n = 11)</td>
<td>10.7 ± 4.8</td>
<td>28.4 ± 3.8</td>
<td>74.5 ± 9.0</td>
</tr>
<tr>
<td>Females (n = 3)</td>
<td>18.1 ± 2.7</td>
<td>25.0 ± 3.0</td>
<td>57.6 ± 4.5</td>
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\(^a\) Body fat was estimated by skinfold measurement by the method of Jackson and Pollock (1977).
LACTATE MINIMUM TESTS

The average plasma lactate concentration at the end of the 8-min rest in the LMT was 12.3 ± 2.8 mM (range: 6.5 to 17.4, with only one test less than 8.7 mM). The minimum lactate concentration during the incremental test ranged from 2.9 to 9.2 mM across the two tests, with average values of 6.3 ± 2.2 mM in LMT1 and 7.0 ± 1.7 mM in LMT2. The range of speeds attained in the sprint efforts was 36.8 to 56.2 km ⋅ hr⁻¹ (136.4 ± 17.4% of the average 20-km time-trial speed). In all cases but one, subjects were able to complete a sufficient number of increments in the LMT to obtain a decreasing, then increasing, lactate profile (see Figure 2 for sample). In this single case the test was repeated, and the subject was asked to give less effort during the initial sprints. Otherwise the test was done according to the original design. The data were fit to a second order polynomial equation ($r^2 = 0.95 ± 0.05$). Estimation of the LMS was done by differentiation of the equation, and solving for the equation equal to zero. LMS was also estimated by simply taking the speed at which plasma lactate was the lowest during the incremental test. The difference between the LMS estimated by regression analysis and by selecting the speed with the lowest lactate was 0.2 ± 0.7 km ⋅ hr⁻¹ for LMT1 and 0.1 ± 0.7 km ⋅ hr⁻¹ for LMT2, indicating general agreement between these two methods of selecting the LMS. In general, subjects reached their lactate minimum between the third and fifth stage, but individual results varied from the second to the sixth stage.

With the exception of two subjects, there was very good agreement between LMT1 and LMT2 (see Figure 3). A Bland and Altman style analysis (Bland and Altman, 1986), demonstrates that there is no slope ($r^2 = 0.0595$) for the regression of difference between tests and the average of the two trials. There is also no offset, indicating no learning effect for this test.
**Figure 2.** Plasma lactate concentration vs. speed during a LMT. Plasma lactate concentration falls at low speeds, reaches a minimum (at LMS) then increases as speed of the incremental test increases. The line represents the best fit to a second order polynomial equation: Lactate = 0.25 · speed² - 16.8 · speed + 284.9 ($r^2 = 0.884$). Initial plasma lactate (after the 8-min rest), was 12.7 mM.

**Figure 3.** The reproducibility of a test is best evaluated by comparing the average of the two trials with the difference between the two (Bland and Altman, 1986). A significant offset (test 1 consistently different from test 2) would indicate a learning effect of the test. A significant slope would indicate a pattern of difference that would be hidden with a comparison of mean values. This would be the case, for example, if only those with particularly low results improved on the second test. The fact that the difference between tests is scattered about zero across the full range of mean values indicates good agreement between tests with no consistent variation.
Heart rate always increased linearly with respect to speed during the incremental tests ($r^2 = 0.94 \pm 0.05$ for LMT1 and $0.96 \pm 0.03$ for LMT2). The heart rate at the LMS was estimated using the linear regression of heart rate vs. speed, and substitution of the LMS in the resulting equation. This gave a mean heart rate at LMS of $162 \pm 10.5$ beats·min$^{-1}$ for LMT1 and $160.5 \pm 12.0$ beats·min$^{-1}$ for LMT2. Although these means were not significantly different ($p > 0.25$), this lack of difference stems from considerable variability rather than consistent similarity ($r^2 = 0.61$).

CONSTANT SPEED RIDES

Four constant speed rides were completed by each subject in this study. The lowest speed ride for which there was a plasma lactate concentration increase of $\geq 0.7$ mM during the last 20 min of the test was first identified and designated as MLSS+. The next slowest ride, which must be equal to or slower than the MLSS intensity, was referred to as the apparent MLSS (MLSS). This differentiation was made because it is not possible to identify the exact speed at MLSS, which lies in between the MLSS and MLSS+. The individual velocities of the MLSS and MLSS+ rides are presented in Figure 4, where they are plotted against the (average) LMS. To determine the accuracy of prediction of the LMS, a comparison of means was done with ANOVA (MLSS vs. LMS1 vs. MLSS+). A significant difference was found, and posthoc analysis with Newman Keuls test revealed that MLSS+ ($34.2 \pm 3.0$) was significantly greater than both MLSS ($33.5 \pm 3.1$) and LMS1 ($33.6 \pm 3.5$; $p < .005$). There was no significant difference between LMS1 and MLSS ($p > 0.9$). Analysis of the mean values conceals the fact that there were three subjects for whom the LMT did not provide a good estimate for MLSS (see Figure 4). Two of

![Figure 4.](image-url) Average LMS (average of two trials) is plotted with two of the constant speed rides: MLSS (diamonds) and MLSS+ (circles). The solid line is the line of identity. The line should fall between the diamond and the circle for any given subject. There are three subjects for whom LMS was not a particularly good estimate of MLSS.
these subjects are shown as outliers in Figure 3 (greater difference than one km·h⁻¹ between LMT1 and LMT2). One of the LMTs for these two subjects was apparently not a good test. These two tests were the only ones for which the lowest lactate during the LMT was reached on the second stage of the LMT.

Heart rate did increase significantly (p < 0.05) from 10 min (160 ± 4 beats·min⁻¹) to 30 min (163 ± 11 beats·min⁻¹) at the intensity designated as MLSS, but increased to a greater extent at the speed just slightly higher (MLSS+), from 165 ± 10 to 173 ± 10 beats·min⁻¹ (p < .02).

The average plasma lactate concentration at MLSS was 7.06 ± 2.5 mM after 10 min and 6.7 ± 2.0 mM after 30 min (range at 30 min: 3.3 to 9.8 mM). At MLSS+, an average speed just 0.9 ± 0.9 km·h⁻¹ faster than the speed at MLSS, plasma lactate concentration was 7.1 ± 1.7 mM at 10 min and 8.7 ± 2.1 mM at 30 min (p < .001).

Figure 5 illustrates individual plasma lactate change during the constant speed trials and difference in speed from the LMS. Values to the right of the vertical axis (at zero difference) represent speed in excess of LMS. Note that plasma lactate did not increase by 0.7 mM or more when the speed of the constant speed ride was at or below the LMS. Also, eight subjects were able to ride at speeds in excess of their LMS without apparent lactate accumulation. Figure 6 illustrates the speed

![Figure 5](image_url)

**Figure 5.** Change in plasma lactate concentration from 10 min to 30 min vs. difference between LMS and the constant speed rides (constant speed – LMS). The vertical axis is at 0, corresponding to constant speed ride at speed = LMS. To the left of the vertical line, all data points fall at or below 0.5 mM change in plasma lactate concentration. To the right of the vertical line, most data points are above 0.5 mM change in plasma lactate concentration. Circles represent the slowest ride for which a change of plasma lactate of at least 0.7 mM occurred from 10 to 30 min of a constant speed ride (MLSS+). Diamonds represent the fastest ride that was slower than the corresponding circle (MLSS). Squares represent a speed slower than the corresponding diamond. The x represents rides faster than the lowest speed for which a change of at least 0.7 mM was observed. True MLSS should be between the diamonds (MLSS+) and the circle (MLSS) for any subject. The horizontal dashed line indicates 0.7 mM increase in plasma lactate.
and plasma lactate concentration during some of these constant speed rides. With the exception of one subject, a constant speed was maintained during these trials. This constant speed was higher than the speed at which a minimal increase in plasma lactate of 0.7 mM had occurred during the final 20 min of a 30-min ride, yet plasma lactate did not appear to be accumulating. There was no relationship ($r^2 = 0.08$) between plasma lactate concentration and speed at MLSS.

**Discussion**

The purpose of this study was to evaluate the reliability and validity of the LMT for cycling, and to evaluate this measure as a predictor of cycling endurance performance. The results show that the LMT, performed using one’s own bicycle on rollers set to simulate road conditions, is reliable and is a valid predictor of MLSS and 20-km time-trial performance. Not only was the test highly reproducible, the test gave a very accurate prediction of the intensity of exercise at MLSS (see Figure 4).

There are three main reasons for wishing to identify the intensity of exercise above which there is a net contribution from anaerobic metabolism: evaluation of endurance capability, designation of individual training intensities and assessment of the effectiveness of a training program. Determination of the MLSS is one of the most appropriate measures of this transition intensity, as MLSS avoids subjective data interpretation and lack of methodological standardization that are evident in many of the "threshold" measurements. However, estimation of the MLSS requires a minimum of two testing sessions (but often requires 3–4 testing sessions).
For this reason, a single-day test to predict the MLSS, such as the LMT, as proposed by Tegtbuer et al. (1993), appears to be a reasonable alternative. In the present study, the precision of estimate was probably helped by the inclusion of a pretest (initial time-trial), which permitted the LMT to be conducted over a very small range of intensities. On the surface, this appears to be a procedure that requires at least two sessions. However, retesting an athlete after a period of training would probably require only the LMT session. It would not be necessary to repeat the time trial, since a starting intensity would already be known for that athlete.

There are several key features of the LMT that must be maintained. These features are related to the magnitude of initial lactate response, duration of the rest interval, initial intensity of the incremental test, and stage duration and increment size in the incremental test. Each of these features will be addressed below.

MAGNITUDE OF INITIAL LACTATE RESPONSE

The nature of the LMT requires that the incremental test be initiated under conditions of lactic acidosis. The initial high intensity efforts must be sufficient to result in relatively high plasma lactate levels, yet allow completion of the remainder of the test. The speeds attained during the sprint efforts in this study represented 136.4 ± 17.4% of the average time-trial speed, resulting in an average plasma lactate concentration of 12.3 ± 2.8 mM after the 8-min recovery period. The lactate concentration values are similar to some previously published values for endurance athletes of 14.0 ± 2.2 mM (Tegtbuer et al., 1993), but higher than others, ranging from 6.1 ± 1.5 to 6.5 ± 0.9 mM depending on the protocol (Carter et al., 1999). In the latter cases, blood lactate concentration approached or reached resting levels during the incremental test. This situation renders the test inconclusive because a lactate decrease could no longer be observed during the incremental test, making it impossible to identify a single speed representing LMS. In the present study, one subject reached a peak plasma lactate value of 17.4 mM during the first LMT (after sprinting at an intensity equal to 158% of their best time-trial speed) and was unable to complete the test. A posteffort blood lactate concentration of approximately 8mM has been recommended in the literature (Carter et al., 1999), but no rationale was provided for that recommendation. There has been no systematic evaluation of the appropriate lactate response, but clearly there is a range of values that permits a valid test. Sampling procedures and measurement techniques (plasma vs. blood) will influence the absolute lactate value that is obtained/appropriate (Bishop et al., 1992; Foxdal et al., 1991, 1994).

DURATION OF THE REST INTERVAL

It is known that blood lactate peaks about 4 to 7 min after exercise that elicits a substantial increase in blood lactate concentration (Medbo and Tabata, 1993). Eight minutes of light, active recovery has typically been used in LMT protocols (Carter et al., 1999; Tegtbuer et al., 1993). The purpose of the 8-min rest is that it permits blood lactate to begin to decrease before the incremental test begins. If blood lactate was still increasing when the test was initiated, then the lactate concentration profile would not likely be a simple decreasing then increasing curve. Therefore, it would probably be a mistake to use a shorter time. A longer time (>8 min) would
increase the likelihood that lower (resting) levels of blood lactate would occur during the incremental test. The active recovery should be conducted at an intensity that is low enough that it is unlikely to result in increased muscle lactate concentration.

INITIAL INTENSITY OF THE INCREMENTAL TEST

Choosing an appropriate initial intensity for the incremental portion of the LMT is also an essential aspect of a valid LMT. We chose to have the subjects do a time-trial, which we assumed would be completed at a speed close to the MLSS. The starting speed of the incremental test was then arbitrarily set at four km·hr⁻¹ less than the average speed maintained during the 20-km time-trial. The important feature here is that the starting point should permit the subject to reach the LMS within three to five increments, so data points are available both above and below the LMS. This feature of the LMT could be interpreted as a limitation. However, since it is unlikely that the LMT will be a once-only test for a given athlete, an appropriate starting point for the test would be known for that athlete on an ongoing basis. In two individual cases in our study, the lowest lactate concentration during the LMT was reached on the second stage of the test. Following identical procedures, a substantially different result was obtained on the other LMT. Clearly, not all factors that affect the test were controlled.

Carter et al. (1999) had endurance runners perform eight LMTs, each with a different starting speed. The speeds were related to each individual’s lactate threshold, determined during a previous incremental test, and ranged from three km·hr⁻¹ below, to one km·hr⁻¹ above the running speed at the lactate threshold. The increment steps were one km·hr⁻¹, and a 10- to 15-s break was taken between each of the 5-min stages for blood sampling. Considerable variability in estimated LMS was shown. The authors concluded that the LMS does not occur at a “critical” exercise intensity representing a MLSS, but rather is indicative of the blood lactate recovery kinetics and the metabolic demand of the preceding exercise interval (Carter et al., 1999). This study clearly demonstrates the advantage of conducting the test with some way of selecting the appropriate initial speed. It has been demonstrated that conducting the test with slight variations in the protocol will yield different results (Carter et al., 1999). The fact that resting concentrations of blood lactate were apparently obtained in the study by Carter et al. (1999) indicates that there may have been additional problems with their protocol, which may have resulted from the relatively low peak blood lactate concentrations obtained in that study.

STAGE DURATION AND INCREMENT SIZE

In this study, the stage duration was dependant upon speed, because the distance covered was held constant at 1500 m. Increment durations ranged from 3.6 min (at 24.8 km·hr⁻¹) to 1.9 min (at 46.3 km·hr⁻¹). For the testing of endurance runners, Tegtburr et al. (1993) found that stages of 800 m (lasting approximately 2.2 to 4.3 min) and 1200 m produced similar LMS values, whereas the LMS was significantly higher with 400 m increments (approximately half the duration of 800 m). Therefore, for practical reasons, stages lasting 3 to 4 min were recommended. In the present study, some of the faster stages were shorter than this recommendation, but they are similar to those in Tegtburr’s work, where the shortest stage lasted 2.2
min. Furthermore, by default the shorter stages occur later in the test, when they would have less impact on the result of the test. Our shorter stages resulted from particularly fast performances by some of our athletes. There may be some advantage in using a fixed duration of stage rather than a fixed distance, but this will need to be evaluated.

Using a fixed distance LMT protocol leads one to question if lactate kinetics are different between the starting and ending stages of the test. It is possible that if the stage duration is not long enough, the plasma lactate concentration may not accurately reflect the metabolic demand of the stage. For the purposes of this research, attainment of steady state during each increment is not necessary. However, the increment duration needs to be long enough to show the direction of net lactate uptake or accumulation.

The increment size during the incremental test is also an important consideration. This is one of the strengths of our study, in that the increment steps of one km·hr⁻¹ were relatively small (ranging from 2.5 to 3.5 % of the estimated LMS). Others have used larger increments. Jones and Doust (1998) used one km·hr⁻¹ increments, representing 6.6 % of the average LMS for treadmill running. Tegtburt et al. (1993) used increments of 0.33 m·s⁻¹, representing 8.6 % of the average LMS. The advantage of using small increments is that the test permits fine resolution of the LMS. Large steps are useful if the test is started at a relatively low intensity, which is appropriate when there is uncertainty regarding the actual LMS. A preliminary test (like a time-trial as we used) can assist in providing more information regarding an appropriate starting speed for the incremental test. Curve-fitting to locate the apparent LMS should permit relatively precise estimation even when the steps are large.

In our study, there was no significant difference in the LMS identified using non-linear regression analysis and the LMS which corresponded to the lowest lactate value during the incremental portion of the LMT. The subjects in this study performed an average of 8.7 increments during the LMT, which may not be necessary given the similarity between the aforementioned methods of LMS determination. The more data points available to predict the LMS, and the smaller the increments, the better the prediction, whether by the second order polynomial or by selecting the speed corresponding to the lowest observed plasma lactate value. As well, the average r² for the prediction equation from the first test was 0.94, and for the second LMT was 0.93. This suggests that there was not a great deal of unaccounted for variance in the equations that were found to predict the speed at which there was no change in lactate concentration.

Carter et al. (1999) refer to five to six stages as being an acceptable number for the LMT, but do not say how many were used in their study. They do not provide references for what appears to be an arbitrary selection of five to six stages. This number of stages (3-min duration) was also apparently used by Jones and Doust (1998). We did not have a fixed number of stages in our study, but subjects completed 8.7 stages on average.

HEART RATE RESPONSES

There was no significant difference in the heart rate at the LMS between LMT1 and LMT2, but some variability did exist. This indicates that exercise heart rate may not be a good indicator of the LMS. However, the heart rate at LMS was very
similar to the heart rate during the constant speed ride at MLSS. Although the heart rate did increase significantly during the ride at MLSS, the increase was very small. Lajoie et al. (2000) made a similar observation. They detected a significant increase in heart rate by 30 min for subjects cycling at the intensity of exercise associated with the MLSS. The heart rate of our subjects increased substantially when the speed of the ride was just slightly higher, indicating an inability to maintain a constant heart rate at exercise intensities greater than MLSS. Tegtbjer (1993) found that the HR at LMS (during the LMT) was almost identical to the HR at 6.4 km of an 8 km run at the LMS. At a speed 0.2 m·s⁻¹ greater than the LMS, there was a significant difference between the HR at LMS and the HR at 6.4 km of a constant intensity run. Although previous studies advocate the use of heart rate for quantification of training intensities (Swensen et al., 1999; Tegtbjer et al., 1993) and MLSS prediction (Palmer et al., 1999), speed based methods may be more specific and more appropriate, due to individual variability in heart rate.

PLASMA LACTATE CONCENTRATION AT MLSS

There was a broad range of values for plasma lactate concentration at MLSS (3.3 to 9.8 mM at 30 min). The average plasma lactate concentration at MLSS was 6.7 mM, which compares favorably with previous studies: 5.4 mM (Swensen et al., 1999) and 8.9 mM (Jenkins and Quigley, 1990) for trained cyclists, and 3.8 mM for endurance runners (Tegtbjer et al., 1993). The absence of any relationship between speed at MLSS and plasma lactate concentration indicates that absolute lactate values are probably not relevant in this test.

CRITERION FOR MLSS

Once an intensity has been defined as one which produces the requisite steady state blood (or plasma) lactate concentration, a subsequent constant load test at a marginally higher intensity should be completed to verify MLSS. If this test produces an increase in blood lactate concentration greater than some recognized criterion, it is assumed that this intensity is above MLSS. The criterion for MLSS attainment is most typically an increase in blood lactate no greater than one mM during the final 20 min of a constant load test (Carter et al., 1999; Heck et al., 1985; Jones and Doust, 1998; Palmer et al., 1999). However, other criteria have been proposed, including a change no greater than 0.2mM during the final 10 min of a 20-min test (Havery et al., 1988) and an increase of not greater than 0.5 mM during the final 20 min of a 30-min test (Aunola and Rusko, 1992). In this study we chose to use 0.7 mM as the criterion change in lactate concentration during the final 20 min of a 30-min ride at constant speed to recognize that the speed has exceeded the MLSS. Although this criterion resulted in good agreement between our LMS and the speed at which blood lactate remained in steady state, there were indications that the MLSS is not a fixed intensity of exercise.

Our data show that eight subjects were able to ride at speeds greater than their MLSS without experiencing lactate accumulation greater than 0.7 mM during the final 20 min of constant load testing (Figure 5). Although it is difficult to know why these subjects were able to cycle at speeds greater than their MLSS without accumulating lactate, it should be noted that plasma lactate was particularly high throughout the test in most of these subjects (Figure 6). It could be that
transport of lactate out of the muscles was a limiting factor preventing progressive accumulation of lactate in the plasma.

The fact that the LMT does not consistently predict MLSS for all individuals is puzzling, and indicates that further research is needed into the reliability and individual variability of the test. Other researchers have had similar findings, such as Bacon and Kern (1999) who reported that the LMT was an accurate predictor of MLSS for 90% of their subjects. This suggests that factors other than the aforementioned test parameters may impact the results. We have observed a test result on a day after vigorous exercise that was substantially different from a previous test for that subject. It may be that testing athletes in a fatigued state leads to inaccurate results. Perhaps there are other factors that must be identified and controlled in subsequent studies.

Conclusion

Determinants of success in physiological based sports, such as cycling and triathlon, include maximal oxygen uptake, the percentage of maximal oxygen uptake that can be sustained, and economy of locomotion. This study focuses on evaluating a method to measure the intensity of exercise associated with maintaining a constant plasma lactate concentration. Maximal lactate steady state has become an attractive concept in terms of predicting endurance performance, prescribing exercise intensity, and monitoring athletes’ progress. Since measurement of MLSS requires a minimum of two (but more realistically, three or four) testing sessions, performed on different days, many attempts at predicting MLSS from a single test have been made. Our study confirms that the LMT is a valid and reliable method for this purpose. The LMT is appealing since it is completed in one testing session. Interpretation of the results is quite straightforward and dependant upon a mathematical function. The use of a pre-test to determine an appropriate starting speed for the incremental portion of the test allows greater confidence in selecting a starting condition for the test. A 20-km cycling time-trial, performed on one’s own bicycle and Krietler rollers, seems appropriate for this purpose for cycling. Although the LMT may have some limitations, it is a valuable addition to the field of “threshold” testing, where agreement has not been achieved despite many years of work. Future research should examine individual variability over time and endeavor to identify other factors that may lead to inaccurate determination of the LMS.

References


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