Individual Anaerobic Threshold and Maximum Lactate Steady State

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Abstract

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The individual anaerobic threshold (IAT) as defined by Stegmann et al. 1981 is determined by using the blood lactate-performance relationship during incremental graded exercise and the immediately following recovery phase. The aim of the study was to investigate the validity of the IAT as a measure for the maximum lactate steady state (max Lass) and the monitoring of endurance training. Sixteen endurance trained athletes ($\dot{V}O_2max$ 60.2 ± 5.0 ml $\cdot$ min^{-1} $\cdot$ kg^{-1}) performed a stepwise increasing test until exhaustion on a cycle ergometer (CE) (increasing by 50 W every 3 min), 14 endurance trained athletes ($\dot{V}O_2max$ 64.9 ± 3.8 ml $\cdot$ min^{-1} $\cdot$ kg^{-1}) performed the multistage steptest on a treadmill (TM) (increasing by 0.5 m $\cdot$ s^{-1} every 3 min) to determine the IAT and the 4 mmol $\cdot$ l^{-1} La-threshold (AT). Afterwards endurance tests (E) limited to 30 min (CE) or 45 min (TM) were performed with intensities of 85, 95, 100 and 105% of the IAT (E85–E105) and with 100% of the AT (AT100) (only on CE) in a randomized order each on different days. Lass was present without premature break-off during E85 (in 30 out of 30 cases), E95 (30/30 cases) and E100 (26/30 cases). At E105 and AT100 (104 ± 7% of IAT) mean La increased continuously and/or led to a premature break-off (in 15/30 cases). All subjects with an AT below their IAT were in Lass during AT100. We conclude that the IAT can be regarded as a reliable estimation of the range of max Lass, although 100% of IAT does not necessarily represent exactly the max Lass in all individuals. Workloads below and at IAT usually are in Lass. An intensity of 95% of IAT seems to be advisable for high intensity endurance training, an intensity of 80–90% of IAT can be recommended for low intensity endurance training.

Key words

Individual anaerobic threshold, endurance exercise, lactate steady state

Introduction

The anaerobic threshold, commonly defined as the performance at a fixed blood lactate concentration of 4 mmol $\cdot$ l^{-1} during stepwise increasing test procedures, is accepted as a measure for the endurance capacity (9,11,17,18,20, 21,24,26–32,34,36). However, if endurance exercises are performed with an intensity referring to 4 mmol $\cdot$ l^{-1} lactate during a stepwise increasing ergometry, a lactate steady state is provable only in some subjects, which only seems to be partially dependent on methodological reasons (such as shorter duration of each exercise step). Especially in highly trained endurance athletes the maximum lactate steady state seems to be reached at lower threshold intensities (9,16,24,26,33). Therefore, conceptions for the determination of individual anaerobic thresholds were developed in recent years (4,5,16,27,29,33).

The individual anaerobic threshold (IAT) as defined by Stegmann et al. (33), is determined from the changes in blood lactate both during and after an incremental exercise test. According to this model, the IAT represents the maximal workload where production and elimination of lactate are in equilibrium so that higher exercise intensities lead to progressively increasing lactate values (33). Previous studies have shown that prolonged exercise at the power output equivalent of IAT is associated with a steady state blood lactate response (Lass) (14,22,28,32,33). The accuracy of the methods used as a valid indicator of a demarcation of the blood lactate response during prolonged exercise, however, has not been documented. The purpose of the present study was to investigate the validity of the IAT as a measure of the max Lass during prolonged exercise with different modes of ergometry.

Material and Methods

All exercises were performed on different days at about the same hour within a period not exceeding 4 weeks. The day before each test no intensive training was allowed. At first, every athlete performed a stepwise increasing test on the cycle ergometer or the treadmill, respectively, dependent on the pursued kind of sport. The IAT (33) in both test procedures was determined according to the changes of the lactate concen-

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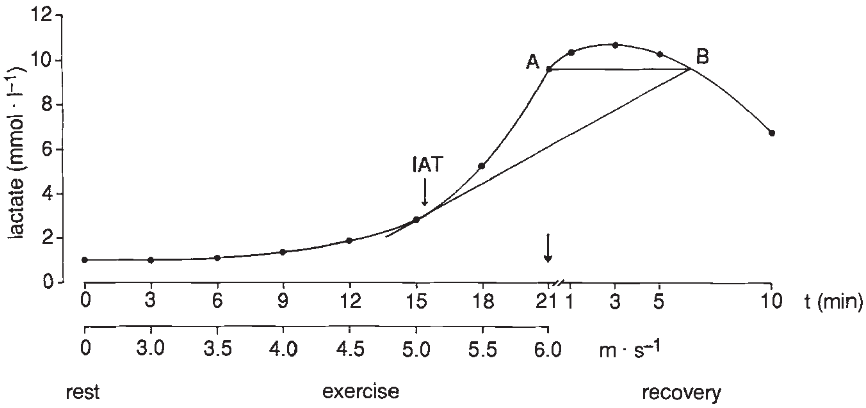

Fig. 1 Lactate kinetics during incremental graded exercise on treadmill. The arrow above the abscissa and the point "A" denote the discontinuation of exercise, "B" the time when the lactate concentration in postexercise period meets the value in "A". The arrow above the curve denotes the IAT.

trations during and after exercise (Fig. 1). In addition, the 4 $mmol \cdot l^{-1}$ lactate threshold (AT) was calculated (21) on the cycle ergometer. After that, 4 or 5 endurance exercises were performed in a randomized order.

Cycle ergometry (CE)

Sixteen well endurance trained male cyclists, triathletes and rowers took part in this study (anthropometric data Table 1). The CE was performed as an incremental graded exercise in a sitting position on an electrically-braked ergometer (Keiper-Dynavit, Kaiserslautern, Germany). It started at 100 W and thereafter increased 50 W every 3 min until exhaustion. Five prolonged exercise sessions (E) of up to 30 min duration were then performed at the exercise intensities of 85, 95, 100 and 105% of IAT (E85–E105) and 100% of AT.

Table 1 Anthropometric data and maximum oxygen uptake ($\dot{V}O_2max$) of the subjects (means ± SD).

	n	age (years)	height (cm)	weight (kg)	$\dot{V}O_2max$ ($ml \cdot min^{-1} \cdot kg^{-1}$)
Cycle ergometer	16	24.6 ±5.6	182 ±7	74.2 ±7.9	60.2 ±5.0
Treadmill	14	28.0 ±5.1	179 ±8	67.7 ±7.9	64.9 ±3.8

Treadmill ergometry (TM)

Fourteen male middle and long distance runners as well as triathletes served as test persons (anthropometric data Table 1). All subjects were familiar with running on a treadmill (Woodway, Lörrach, Germany). The tests were performed with a constant slope of 1.5%. The inclination of the TM differed from the original investigation (5% slope, see ref. 32,33) since internal standardisation has shown 1.5% to present advantages in the transfer of ergometric data on field conditions. The stepwise increasing exercise started at $2.5 m \cdot s^{-1}$ or $3.0 m \cdot s^{-1}$, respectively, and was increased every 3 min by $0.5 m \cdot s^{-1}$ until exhaustion. The E were performed with 85, 95, 100 and 105% of the IAT (E85–E105), after a warm-up with an intensity of 50–70% of the final running velocity. Every 15 min, the treadmill was stopped for 2 min. The duration of E was determined up to 45 min because of the interruptions necessary for blood sampling on TM and because 45 min seems to be more relevant as an exercise duration for endurance running in trained athletes.

During both ergometric procedures the heart rate was determined during the stepwise tests on every exercise level. During the E it was determined every 5 min by means of the "Sporttester" (PE 3000, Polar Electro Finland). Lactate was measured enzymatically in immediately deproteinated (perchloric acid) whole blood from 50 µl capillary samples taken from the hyperemic earlobe (Testomar-Lactat Mono Kit, Behring, Marburg, Germany) (13). The lactate determinations were performed during the stepwise tests without discontinuation (CE) or within the 20 seconds-lasting breaks (TM) between the single steps as well as in the 1st, 3rd, 5th and 10th min of the post-exercise period. During the E, lactate was determined at rest, every 5 min (CE) or 15 min during the breaks (TM) and in the 2nd min after exercise.

A Lass was defined as an increase in lactate of less than $1 mmol \cdot l^{-1}$ between the 10th (CE) or 15th min (TM) and the last blood sample or of less than $0.5 mmol \cdot l^{-1}$ during the last 10 or 15 min.

Mean values and standard deviations were calculated. For the statistical comparisons, an analysis of variance with repeated measurements and t-test for paired data were used (CSS-statistic-program). The level of significance was set at $p < 0.05$.

Results

Cycle ergometry

During the multistage step test, the IAT was 253±42 W corresponding to $3.46 \pm 0.66 mmol \cdot l^{-1}$ lactate. The AT was 104±7% of the IAT. The maximum blood lactate value was measured $11.38 \pm 1.81 mmol \cdot l^{-1}$. An increase of 5% above the workload of the IAT corresponded to approximately 2.8% of $\dot{V}O_2max$.

Lass was present in E85, E95 and E100 (Fig. 2). During E85 the average blood lactate concentrations were between 2.44 (10th min) and $2.29 mmol \cdot l^{-1}$ (30th min), during E95 $3.15–3.12 mmol \cdot l^{-1}$, during E100 $4.20–4.16 mmol \cdot l^{-1}$. None of the test subjects had to break off prematurely during E85, E95 or E100. Only in one subject was Lass not present during E100 until the 30th min.

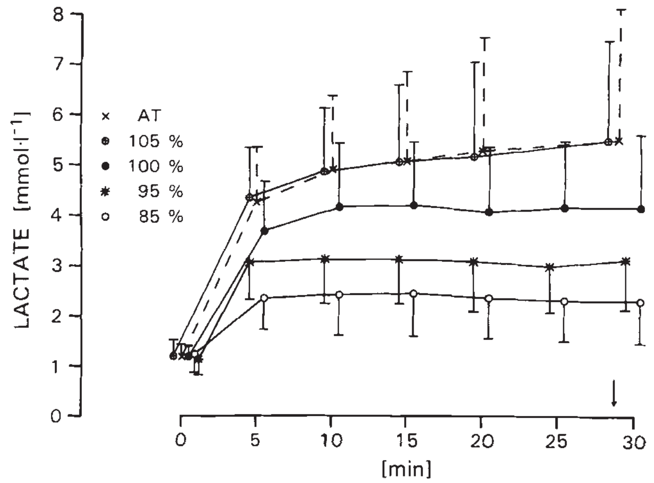

Fig. 2 Blood lactate during endurance exercises on cycle ergometer with an intensity of 85, 95, 100 and 105 % of the individual anaerobic threshold and the 4 mmol · l^{-1} lactate threshold (AT) (n = 16; means ± SD). The arrow denotes the mean exercise time of E105 and AT.

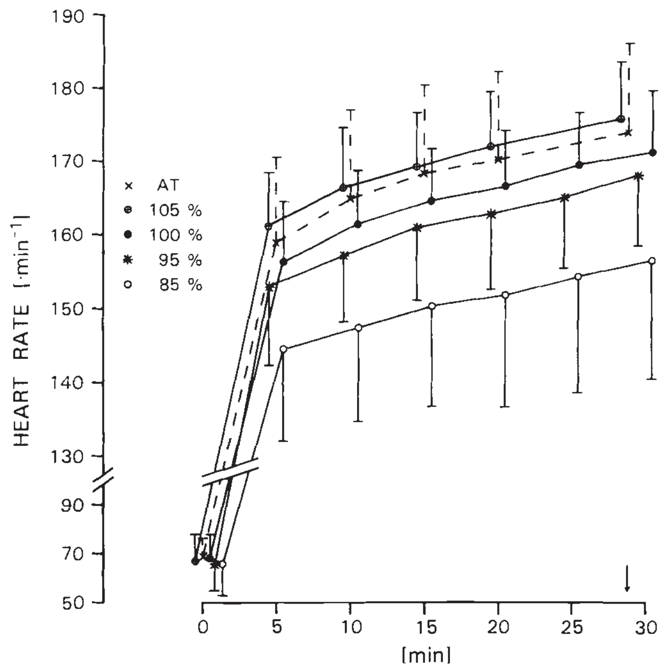

Fig. 3 Heart rate during endurance exercises on cycle ergometer with an intensity of 85, 95, 100 and 105 % of the individual anaerobic threshold and the 4 mmol · l^{-1} lactate threshold (AT) (n = 16; means ± SD). The arrow denotes the mean exercise time of E105 and AT.

During E105 and AT100, lactate increased significantly (Fig. **2**). The course of lactate between all E differed significantly except the comparison between E105 and AT100. Considering the individual changes, two of the subjects had to break off prematurely during E105 and AT100 after 20 and 22 min, respectively, showing the highest blood lactate increases up to 9–10 mmol · l^{-1}. In addition, Lass was not present in 5 athletes. Nine subjects still remained in Lass.

In all four cases, in which the AT was measured below the IAT during the incremental graded test, Lass was present during AT100. In 4 subjects, the lactate at the IAT was below 3 mmol · l^{-1} in the step test. In 3 of these 4 subjects, an E performed with an intensity corresponding to 3 mmol · l^{-1} lactate in the steptest would have been above max Lass and/or led to a premature break-off.

The heart rate increased significantly in the course of all E (Fig. **3**). In contrast to the absolute values, the increase in heart rate, however, did not differ between the E.

Treadmill ergometry

The IAT was 4.29 ± 0.43 m · s^{-1} corresponding to 2.44 ± 0.49 mmol · l^{-1} lactate. The maximum blood lactate value during the stepwise increasing test was measured 8.62 ± 2.18 mmol · l^{-1}. An increase of 5 % above the running speed of the IAT corresponded to approximately 3.5 % of $\dot{V}O_2max$.

During the E the behaviour of lactate was similar to that on the CE. At E85, E95 and E100 Lass was present (Fig. **4**). The mean lactate concentrations were between 1.27 (15^{th} min) and 1.36 mmol · l^{-1} (45^{th} min) in E85, between 2.02 and 2.42 mmol · l^{-1} in E95 and between 3.05 and 3.69 mmol · l^{-1} in E100. One athlete broke off prematurely in the 30^{th} min during E100 while Lass was present, but all the subjects completed the other E with an intensity of 85, 95 and 100 % to the 45^{th} min. In two cases, Lass was not present during E100.

During E105, mean blood lactate was not in a steady state and it increased significantly (Fig. **4**). Five subjects were not able to complete E105, the break-off took place after 13–39 min (22 min on average). During E105 two out of these five subjects showed the highest lactate values of all athletes tested. In three additional cases, a Lass was not reached until the 45^{th} min. A Lass was found in 6 athletes.

In 11 athletes, the lactate concentration at the IAT was below 3 mmol · l^{-1} during the step test. In 5 of these subjects, the results showed that an E performed with an intensity corresponding to 3 mmol · l^{-1} in the stepwise increasing test would have been above the max Lass and/or led to a premature break-off.

The heart rate increased continuously and significantly during all the E. The increase during the 45 min of the tests did not differ between the E (Fig. **5**).

Discussion

According to Stegmann et al. 1981 (33), the determination of the IAT is based on a model that takes into account both the diffusion and the elimination of lactate. The IAT is calculated from the lactate kinetics during stepwise increasing test procedures and the early recovery phase (Fig. **1**). Despite the fact that in a recently published study (21) an influence on the determination of the IAT by an active recovery phase in comparison to a passive one could not be detected (which was explained by an essentially unchanged early elimination of lactate), we support a standardized passive post-exercise period, as proposed by the same authors (21). This was

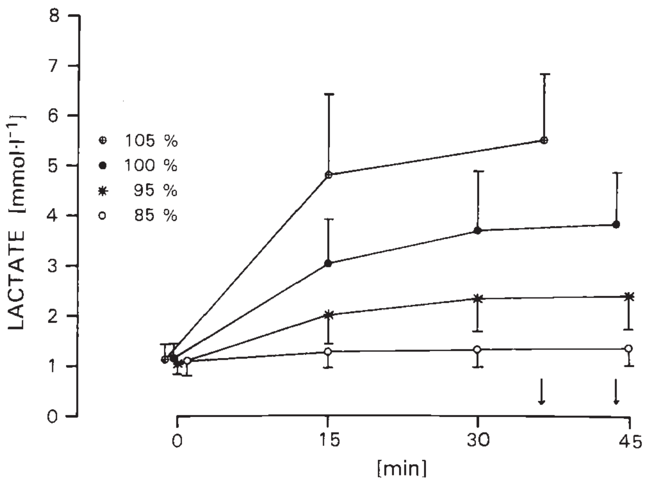

Fig. 4 Blood lactate during endurance exercises on treadmill with an intensity of 85, 95, 100 and 105 % of the individual anaerobic threshold (n = 14; means ± SD). The arrows denote the mean exercise time of E105 and E100.

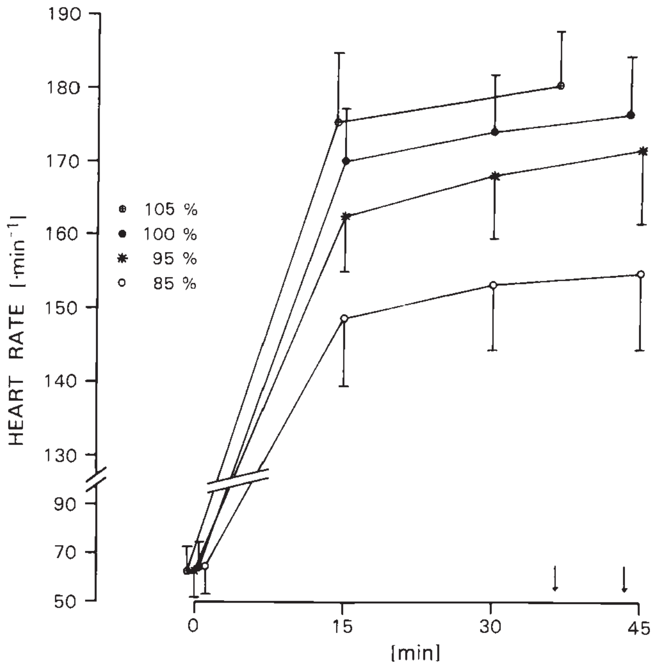

Fig. 5 Heart rate during endurance exercises on treadmill with an intensity of 85, 95, 100 and 105 % of the individual anaerobic threshold (n = 14; means ± SD). The arrows denote the mean exercise time of E105 and E100.

taken into consideration in our study. All the incremental graded tests were performed until volitional exhaustion. Although, according to our experience, a maximum exhaustion is not necessarily required in order to determine the IAT, the maximum blood lactate concentration should usually reach at least 6 mmol · l^{-1} (5 mmol · l^{-1} in well endurance-trained athletes). An accurate estimation of the IAT is not possible or the IAT could be underestimated (23) if the maximum lactate values are lower. Furthermore it was ensured that each subject exercised in standardized conditions as far as previous training and diet are concerned. Although the performance at the IAT is not influenced during graded exercise if working muscles are depleted in glycogen (7), a smaller production of lactate with corresponding overestimation of the performance at 4 mmol · l^{-1} lactate during the stepwise increasing test, a limited anaerobic performance as well as shorter time until exhaustion in endurance exercise is to be expected under these conditions (1,2,7).

The criteria for acceptance of a Lass are not without importance, too. In the present study the definition of Lass represents a compromise between the increases of 0.2 and 1.0 mmol · l^{-1} proposed by other authors (9,10). The consideration of the behaviour of La during the two last blood samples takes into account the fact that the time interval for adjustment of a Lass increases with the intensity of work (20). In a recent investigation (35), it was concluded that the ventilatory threshold gives the max Lass because of the statistically significant but rather small increase of lactate (approximately 0.3 mmol · l^{-1}) in 8 subjects performing prolonged exercises at a workload 4.9 % above the ventilatory threshold. The analysis of the individual lactate curves, however, reveals that only 2 subjects would have exceeded our criteria of Lass at this exercise intensity.

The results show that E performed with an intensity of 100 % of the IAT or below usually are in Lass. This was true for 96 % of our subjects, which corresponds to previous investigations (14,28,32). On the other hand, intensities above the IAT led to a distinct increase in the number of athletes showing progressive lactate acidosis and premature break-off. This applied to already half of the examined subjects when the IAT was exceeded by only 5 %. Early abandon certainly depends on the individual ability to tolerate higher acidosis; however, in both ergometric procedures, the two athletes showing the highest lactate values during prolonged exercise have not been able to finish E105 and AT100.

In methodically extensive studies it could be demonstrated that the mean values of IAT correspond to the range of max Lass, if the increase of work load in the incremental graded test used for determination of the IAT exceeds 17 W min^{-1} (9,11), as applied in the present study. In contrast to our results, the authors reported this test scheme to overestimate the mean value of max Lass by less than 3 %, which represented the best estimation of max Lass of the lactate threshold concepts investigated.

For methodical reasons it will be hardly possible to delineate the range of max Lass more precisely than by steps of 5 %. Furthermore it will be rather difficult to investigate the transfer of our results to not endurance-trained persons because of intercurrent training effects when performing repeated bouts of prolonged exercise.

In spite of having chosen relatively well-trained athletes, an effect of training could not be avoided in some subjects in the course of the investigation. Although this could explain that some E105 performed at the end of the study according to the individual randomized order remained in Lass, 100 % of IAT seems not to represent exactly max Lass in all individual cases. One explanation could be that the assumption of a maximal elimination rate of lactate was not always valid

(25,33). However, it remains unclear whether this is of practical relevance during the early recovery phase (23,25,33): Although it is known that light workloads after onset of exercise enhance lactate removal from blood (6,8,23), the calculation of IAT has been reported to be unaffected (23).

At our institute, 95–100% as well as 110% of the IAT have been accepted as standardized intensities for exhausting E for years. When performing at the former intensity, the number of premature break-offs before the 50 min or of missing Lass is under 5%. At 110% IAT on the CE less than 3 % of the endurance trained subjects remained in Lass (unpublished results).

Fixed lactate concentrations as a basis for threshold concepts, such as 4 $mmol \cdot l^{-1}$, originally represent *mean* steady state values (precisely 4.02–4.32 $mmol \cdot l^{-1}$) (9,11). They depend on precisely defined test protocols and maybe also on state of training (9,11,21,24,26). Even when using the original recommended test program with a step duration of 4 or 5 minutes, it can be expected in some cases that the corresponding intensity of endurance tests is above max Lass. A shorter step duration, e.g. 3 min, leads to a higher performance at 4 $mmol \cdot l^{-1}$ lactate, which is more often above max Lass during the corresponding E. This could be confirmed in the present study as well as in many other studies (9,14,24,26,32,33). Our results show that even a fixed concentration of 3 $mmol \cdot l^{-1}$, as it is sometimes suggested as corresponding value to the AT when using steps of 3 min each (9), cannot be valid for max Lass as well, since 9 out of 15 athletes showing an IAT below 3 $mmol \cdot l^{-1}$ would have been above max Lass or break off prematurely. Inversely, Lass was present in all cases in which the AT was measured lower than the IAT in the corresponding E (AT100).

Lactate concentrations are lower by approximately 1 $mmol \cdot l^{-1}$ in TM than in CE at the IAT during the steptest as well as during E with the same percentage of intensity of the IAT. This could be due to the better aerobic state of training of the athletes (presenting higher $\dot{V}O_2max$) who exercised on the treadmill or to the larger muscle groups involved in running. The interruptions for blood sampling on TM (20 s for the incremental graded test, 2 min during E) cannot explain entirely the extent of the observed discrepancies (9).

As already stated by other investigators, too, the differences between the lactate values at IAT during the incremental graded test and during the endurance exercises do not argue against the concept of IAT because the determination of IAT do not request a lactate steady-state (9,23,32,33).

The present study underlines the results from systematic investigations under field conditions (3), suggesting that the IAT could be an instrument which is relevant in training practice in order to aim at defined lactate ranges. For that reason, we indicate ranges of 92–100% or 80–92% of the IAT (3) as guidelines for high intensity (so-called "intensive") or low intensity (so-called "extensive") endurance training. It has to be pointed out, however, that these recommendations need further evaluation under field conditions because of external factors of influence in training which cannot be simulated by TM or CE. This restriction also applied to the verification of a *max* Lass in the range of 100–110% of IAT.

Other attempts for monitoring the intensity of prolonged exercise lasting 15–30 min used percentages of heart rate (34). The authors also refered to ranges of blood lactate concentrations commonly suggested as workload to improve performance (3,11,12,18,28,29,31,34). However, from the strictly scientific point of view, it has not been finally proven whether lactate diagnostic itself is able to give distinct results. The present study as well cannot demonstrate that the IAT represents an optimum of endurance training intensity. This would need extensive long-term studies. Besides, it is doubtful whether a training in the range of max Lass, which is characterized by individually quite different lactate values (9,20,25, 26,32), always leads to the same aerobic training effect. Yet, our systematic studies are an attempt to examine theoretical concepts under practice conditions.

In summary, the results of the present study show that the IAT allows a reliable orientation of the range of max Lass. However, 100% of IAT does not necessarily represent exactly the max Lass in all individual cases. Prolonged exercises performed with intensities of the IAT or below usually are in Lass. When exceeding the intensity of the IAT by only 5 %, in half of our subjects a progressive accumulation of lactate or a premature break-off was measured. Workloads of about 95 (92–100)% and 85 (80–92)% of the IAT seem to be advisable for guiding the endurance training when using the commonly recommended exercise intensities.

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