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Reliability, reproducibility and validity of the individual anaerobic threshold

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Summary. The individual anaerobic threshold (IAT) has been defined as the highest metabolic rate at which blood lactate (La) concentrations are maintained at a steady state during prolonged exercise. The validity of this definition, however, has not been substantiated. Eleven men [maximum oxygen uptake ($\dot{V}O_{2max}$), mean (SD), 57.8 (6.9) $ml \cdot kg^{-1} \cdot min^{-1}$) did two maximal incremental cycle exercise tests (30 W and 4 min per step). Blood was sampled repeatedly during exercise and for 9 min during the subsequent recovery period with light activity. The subjects then exercised at the power output equivalent of IAT for 45 min, until they could no longer continue or until rectal temperature reached 39° C. Subjects performed two additional exercise tests. The intensity of these tests depended upon the LA and acid-base responses during the last 15 min of at least 30 min of exercise at IAT. If a steady state was achieved (La, *pH* and PCO_2 changed by less than 0.5 $mmol \cdot l^{-1}$, 0.005 *pH* units and 0.3 kPa, respectively) or decreasing La and increasing pH values were observed, then the second test was performed at IAT+5% $\dot{V}O_{2max}$ and the third session at either IAT+2.5% or +7.5% $\dot{V}O_{2max}$. Conversely if a steady state was not achieved during exercise at the calculated IAT, the intensity of the second test was set at IAT−5% $\dot{V}O_{2max}$. Depending on the La and acid-base responses during this test, the final session was performed at either IAT −2.5% or −7.5% $\dot{V}O_{2max}$. Test-retest reliability for the determination of IAT was high ($r=0.98$; estimated SE was 8 W or about 2% $\dot{V}O_{2max}$) and the method was reproducible [mean (SD); 240.3 (41.7) W for test 1 and 236.6 (42.9) W for test 2]. However, only 4 subjects completed at least 30 min of exercise at IAT with steady-state La and acid-base responses. None of these subjects showed steady-state responses at +5% $\dot{V}O_{2max}$ above IAT, and only 1 met the criteria at +2.5% $\dot{V}O_{2max}$ above IAT. Therefore, for these individuals the incremental exercise test underestimated the "true" IAT by less than 5% $\dot{V}O_{2max}$. For the other 7 subjects, 4 met the steady-state criteria at both −5% and −2.5% $\dot{V}O_{2max}$ below the calculated IAT, suggesting the true IAT was overestimated by less than 2.5% $\dot{V}O_{2max}$. For 2 of the remaining subjects, the incremental exercise test overestimated the true IAT by at least 7.5% $\dot{V}O_{2max}$. Therefore, the maximal incremental exercise test followed by a light active recovery period will produce a reliable and reproducible estimate of IAT which is valid for the majority of subjects. However, since the method overestimates the true IAT for some individuals, the procedure cannot be assumed (without verification) to be valid for all subjects.

Key words: Blood lactate – Acid base – Steady state – Prolonged exercise

Introduction

Stegmann et al. (1981) defined the individual anaerobic threshold (IAT) as the metabolic rate where the elimination of blood lactate (La) during exercise is both maximal and equal to the rate of diffusion of La into the blood. In theory, the IAT represents the highest metabolic rate associated with a steady-state blood La response during 30–45 min of submaximal continuous exercise (Stegmann et al. 1981). Exercise at power outputs above IAT should result in a progressive metabolic acidosis and exercise time to exhaustion should be inversely related to the amount that the exercise work rate exceeds IAT (Stegmann and Kindermann 1982).

The determination of IAT involves the measurement of blood La during a progressive incremental exercise test and a subsequent recovery period. Results from previous studies have shown that exercise at IAT is associated with a steady-state blood La response (Keith et al. 1992; McLellan and Jacobs 1989; McLellan et al. 1991; McLellan and Cheung 1992; Stegmann et al. 1981; Stegmann and Kindermann 1982). However, these investigations did not examine whether or not

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exercise at a power output slightly above the calculated IAT also resulted in constant blood La levels. Jacobs et al. (1990) reported that 30 min of exercise at metabolic rates 20 W above IAT, calculated from a submaximal incremental test protocol, was associated with steady-state La values. As a result of these findings, we examined the influence of a maximal rather than a submaximal incremental test on the determination of IAT (McLellan et al. 1991). The maximal test protocol was associated with IAT values that were 30 W or 10% of maximal oxygen uptake ($\dot{V}O_{2max}$) higher than IAT calculated with the submaximal test (McLellan et al. 1991). The validity of IAT calculated with this maximal incremental test protocol has not been substantiated.

Individual differences in endurance performance may be related strongly to differences in the metabolic rate that is associated with a maximal steady-state blood La response (i.e., IAT; Stegmann and Kindermann 1982). It would be worthwhile, therefore, to know whether the incremental test protocol that we have recommended for the determination of IAT (McLellan et al. 1991) indeed produces a valid estimate of this "threshold" as defined by Stegmann et al. (1981). As a result, the purpose of this investigation was to examine the validity of the IAT determined from a maximal incremental exercise test and subsequent light active-recovery period. It was hypothesized that if the IAT does indeed represent a "threshold", then exercise at power outputs slightly above IAT (i.e., IAT+5% $\dot{V}O_{2max}$) would not produce a steady-state blood La response.

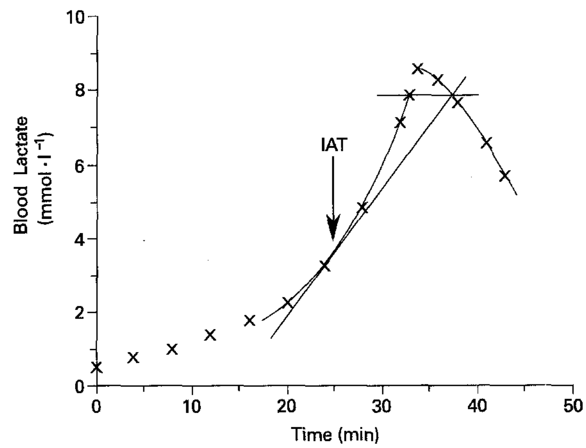

Fig. 1. An example of the blood lactate response during the maximal incremental exercise test and the light active recovery period. The *arrow* indicates the time during the incremental test corresponding to the individual anaerobic threshold (IAT)

Methods

Subjects. Following the approval of the Institute's Ethics Committee, written informed consent was obtained from 11 men [mean (SD); 25.7 (4.1) years; 71.5 (8.2) kg; 1.77 (0.05) m; $\dot{V}O_{2max}$, 57.8 (6.9) $ml \cdot kg^{-1} \cdot min^{-1}$] who volunteered to participate in the study. Subjects were instructed not to consume any food or beverage for at least 4 h before each testing session. A minimum of 5 days separated exercise tests which were performed at the same time of day for a given subject.

Incremental exercise tests. Subjects performed two maximal step-incremental exercise tests on an electrically braked cycle ergometer (Ergomed 930, Siemens). These tests involved continuous exercise which began at 60 W or 90 W (depending on the subject's $\dot{V}O_{2max}$) and increased every 4 min by 30 W. Blood samples taken from a hyperaemic earlobe during the last 30 s of each power output increment were immediately assayed for unlysed whole blood La with an automatic analyser (YSI Model 23A). Both maximal incremental exercise tests were followed by a recovery period of light activity at 60 W. For one subject whose $\dot{V}O_{2max}$ was less than 3.0 $l \cdot min^{-1}$ active recovery was performed at 30 W. Blood samples were taken at 0.5, 1, 2, 3, 5, 7 and 9 min of recovery. One week prior to the first maximal step-incremental test, subjects performed at 30 $W \cdot min^{-1}$ ramp-incremental test to determine $\dot{V}O_{2max}$.

Determination of IAT. Individual data points for both the exercise and recovery La values were plotted as a continuous function against time (Fig. 1). The increasing portion of the exercise La curve was fitted with a single exponential function. The recovery La curve was fitted with a third order polynomial which minimized the residual sum of squares. The residual variance was less than 3% during exercise and 1% during recovery with the use of the mathematical functions described above. From the equation describing the recovery La curve, the time associated with a La value equal to the end of exercise La was calculated. Once the values of these time, La co-ordinates in the recovery period were known, time and La co-ordinates could be calculated that defined IAT. The IAT coordinates satisfied the equation describing the exercise La curve; in addition, the IAT co-ordinates were defined by a line passing through the recovery co-ordinates with the slope of this line also defining the slope of a tangent to the exercise La curve.

Prolonged exercise tests. An average time co-ordinate describing IAT from the two incremental tests was converted to power output and oxygen uptake ($\dot{V}O_2$) since a linear relationship was observed among these variables. Subjects then exercised for 45 min, until they could no longer continue or until rectal temperature reached 39° C at the power output equivalent of IAT. A 5-min warm-up at 30 W preceded this exercise session. Blood samples were taken at rest, following the warm-up and at 5-min intervals during exercise from a 21-gauge catheter (Surflo) inserted into a dorsal hand vein. The technique of heating the hand and forearm in a heating chamber to obtain arterialised venous blood samples has been described previously (McLellan et al. 1991; McLellan and Cheung 1992). A 1.0 ml blood sample was collected in a heparinised plastic syringe, capped, placed in an ice bath and analysed immediately for La (as described above) and for *pH* and PCO_2 by a *pH* and blood gas analyser (Corning 168) which had been calibrated previously with precision buffers and gases of known composition. Core temperature was monitored throughout exercise from a rectal probe inserted approximately 10 cm beyond the anal sphincter. Changes in rectal temperature were used to correct pH and PCO_2 values measured at 37° C by the blood gas analyser. Subjects performed two additional exercise tests. The intensity of these sessions was dependent upon the blood La and acid-base responses during the last 15 min of at least 30 min of exercise at IAT. For example, if La, *pH* and PCO_2 changed less than 0.5 $mmol \cdot l^{-1}$, 0.005 pH units and 0.3 kPa, respectively, during this 15-min period then this response was accepted as a steady state. The intensity of the next exercise session, therefore, was set at IAT+5% $\dot{V}O_{2max}$. The intensity of the final test would be at either IAT+2.5% (if a steady state was not evident at IAT+5%) or IAT+7.5% $\dot{V}O_{2max}$ (if a steady state response was observed at IAT+5%). Conversely, if the subject's response at IAT did not meet the criteria for a steady-state for blood La and acid-base, then the second test was performed at IAT−5% $\dot{V}O_{2max}$. The intensity of the third session was either

IAT−2.5% or −7.5% $\dot{V}O_{2max}$. Obviously, from this design all subjects would not necessarily complete three exercise tests at the same relative intensities. However, we felt that it was important to assess the accuracy and validity of the IAT determination individually.

Gas exchange analyses. For all testing sessions, subjects breathed through a low-resistance Hans-Rudolf respiratory valve. Expired gases were directed into a 5 l mixing box and through a turbine (Alpha Technologies VMM 110 Series Ventilation Module) for the determination of minute ventilation ($\dot{V}_E$). A sampling line directed dried gases from the mixing box to an O_2 (S-3A Applied Electrochemistry) and CO_2 (CD-3A Applied Electrochemistry) analyser. The gas analysers were calibrated before each test with a precision-analysed gas cylinder with known $O_2$and CO_2 composition while the turbine was calibrated with a syringe of known volume. After conversion of the analogue voltage outputs from the ventilation module and the gas analysers into digital signals (Hewlett-Packard 59313 A/D Converter) $\dot{V}_E$, carbon dioxide output and $\dot{V}O_2$ were calculated and printed on-line every 60 s using appropriate software on a microcomputer (Hewlett-Packard 9825A). Heart rate was monitored by telemetry (Sport Tester, PE 3000) and recorded during the last 15 s of each power increment of the incremental exercise tests and at 5-min intervals throughout the prolonged exercise tests.

Data analyses. Test-retest reliability and reproducibility of IAT determined from the two incremental exercise tests was assessed using a Pearson-product moment correlation and dependent *t*-test analysis, respectively. A repeated measures ANOVA was used to examine the gas exchange, blood La, *pH* and PCO_2 responses during the prolonged exercise test at the power output equivalent of IAT. When a significant *F*-ratio was obtained a Newman-Keuls post-hoc comparison was made to clarify the differences among treatment means. For all statistical analyses, the $P<0.05$ level of significance was used.

Site of blood sampling. Six men [28.3 (2.0) years; 84.7 (9.2) kg and 1.80 (0.03) m performed an incremental cycle ergometer exercise test (i.e., 30 W increments every 4 min) followed by a 10-min period of active recovery at 60 W. Blood samples were obtained at the same time from the earlobe and a dorsal hand vein using the procedures described above.

Results

Figure 2 presents the test-retest reliability of the calculation of the power output equivalent of IAT. The standard error of estimate of 8 W represents approximately 0.1 $l \cdot min^{-1}$ or 2% $\dot{V}O_{2max}$ for these subjects. There was no difference between the mean values of IAT determined from test 1 [240.3 (41.7) W; 3.16 (0.64) $l \cdot min^{-1}$ and 76.1 (5.8)% $\dot{V}O_{2max}$] or test 2 [236.6 (42.9) W; 3.15 (0.66) $l \cdot min^{-1}$ and 75.7 (5.6)% $\dot{V}O_{2max}$].

Only 4 subjects completed at least 30 min of exercise at the IAT (Fig. 3). For these individuals, their next prolonged exercise test was at +5% $\dot{V}O_{2max}$ and

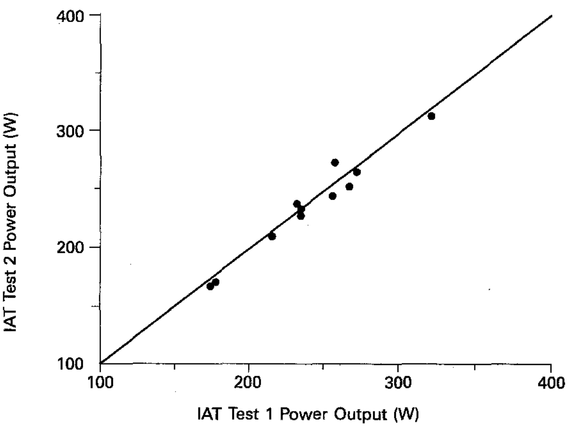

Fig. 2. Individual data points for the power output equivalents of the individual anaerobic threshold (IAT) determined from the two incremental exercise tests. The *solid line* represents the line of identity. The test-retest reliability coefficient was 0.98 and the standard error of estimate was 8.04 W

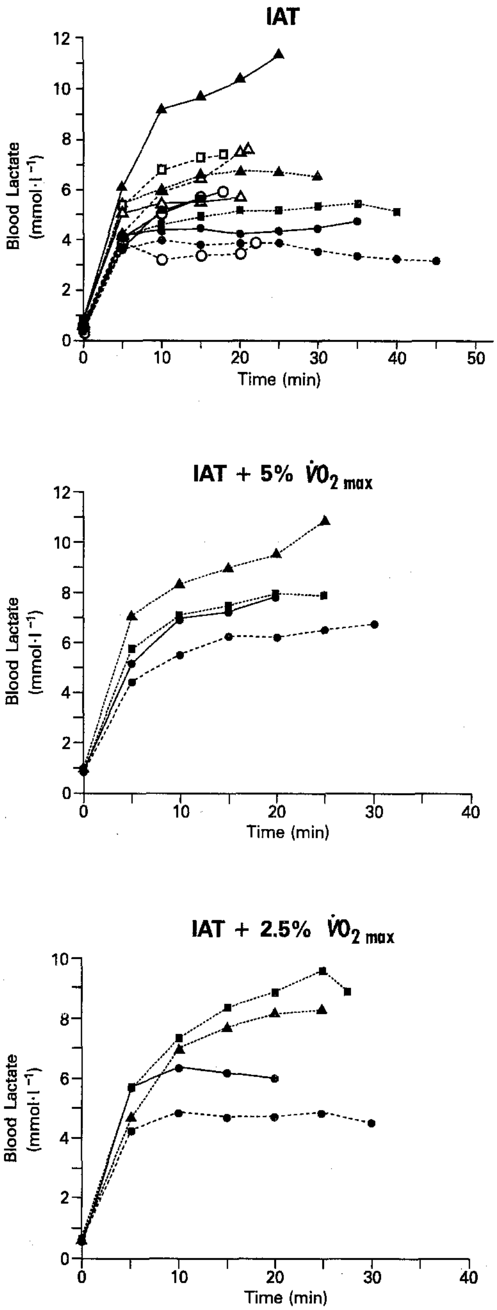

Fig. 3. Individual blood lactate responses during the prolonged exercise test at the individual anaerobic threshold (IAT) for all 11 subjects and, subsequently, for 4 individuals at +5% and +2.5% $\dot{V}O_{2max}$ above IAT. Each *line* represents one subject —●— sub 1; ···●··· sub 2; —○— sub 3; ···○··· sub 4; —▲— sub 5; ···△··· sub 6; —△— sub 7; ···△··· sub 8; ···■··· sub 9; —■— sub 10; ···□··· sub 11

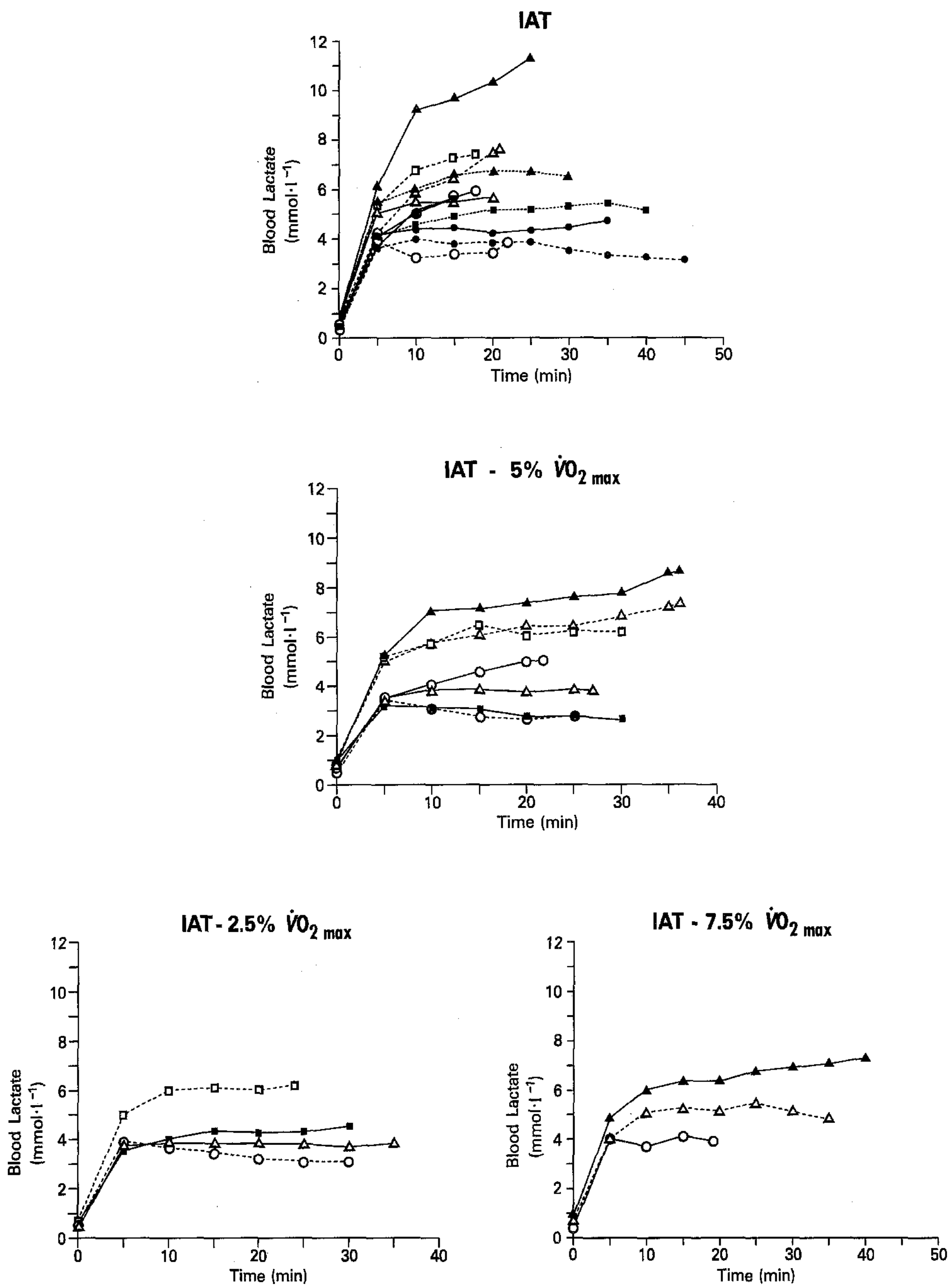

Fig. 4. Individual blood lactate responses during the prolonged exercise tests at the individual anaerobic threshold (IAT) for all 11 subjects and then for 7 individuals at −5% and either −7.5% or −2.5% $\dot{V}O_{2max}$ below IAT. For symbols see Fig. 3

then +2.5% $\dot{V}O_{2max}$ above IAT. The other 7 subjects performed their second prolonged exercise test at 5% $\dot{V}O_{2max}$ below IAT. Following this session, 3 subjects performed their last test at 7.5% $\dot{V}O_{2max}$ below IAT and the other 4 at 2.5% $\dot{V}O_{2max}$ below IAT (Fig. 4).

For 8 subjects who completed 20 min of exercise at IAT, $\dot{V}O_2$ increased to 3.34 (0.44) $l \cdot min^{-1}$ at 10 min but did not increase significantly by 20 min [3.39 (0.46) $l \cdot min^{-1}$]. Similarly, La and *pH* did not change significantly from 10 min [5.37 (1.81) $mmol \cdot l^{-1}$ and 7.294 (0.037), respectively] to 20 min of exercise [5.93 (2.26) $mmol \cdot l^{-1}$ and 7.282 (0.056), respectively].

None of the subjects demonstrated a steady-state response for blood La (Fig. 3) or *pH* (Fig. 5) during the exercise test at IAT+5% $\dot{V}O_{2max}$ and only 1 individual met the criteria at IAT+2.5% $\dot{V}O_{2max}$. For the other 7 subjects, 4 met the steady-state criteria at both −5% and −2.5% $\dot{V}O_{2max}$ (Figs. 5, 6 for La and pH, respectively). Two of the remaining subjects did not demonstrate a steady-state response even at 7.5% $\dot{V}O_{2max}$ below the IAT.

There was no difference at rest, during incremental exercise or during light active recovery for blood La values obtained from heating the earlobe or a dorsal hand vein (Table 1). Similarly, there was no difference in the IAT determined from blood samples obtained from the earlobe [191 (39) W] or a dorsal hand vein [193 (37) W].

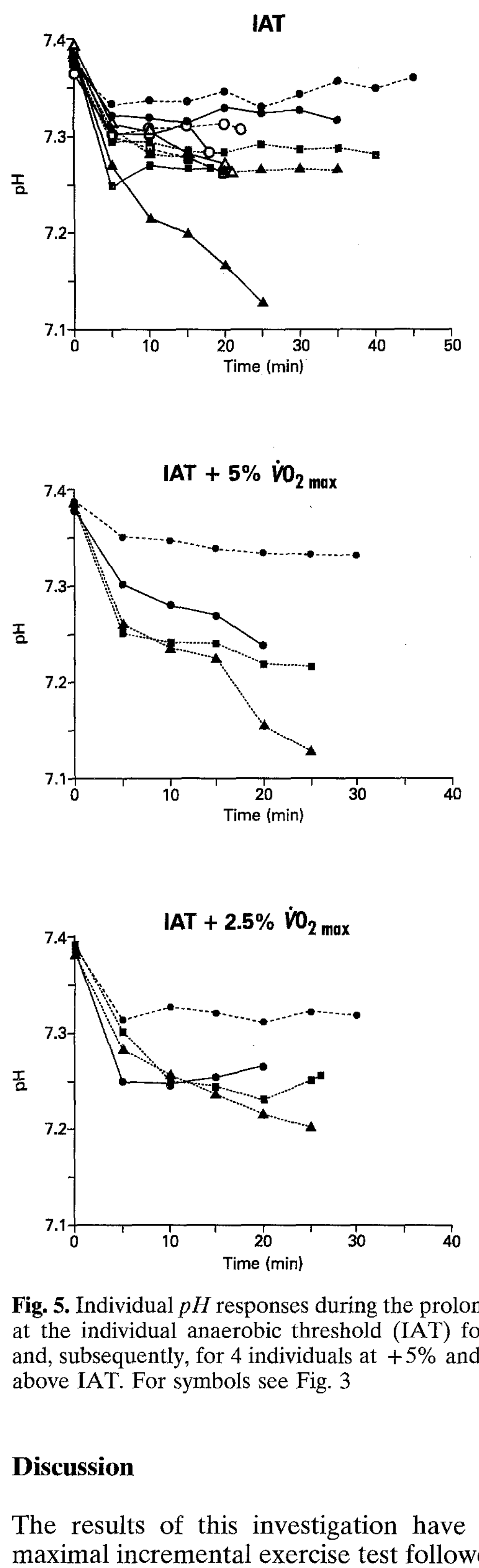

Fig. 5. Individual *pH* responses during the prolonged exercise test at the individual anaerobic threshold (IAT) for all 11 subjects and, subsequently, for 4 individuals at +5% and +2.5% $\dot{V}O_{2max}$ above IAT. For symbols see Fig. 3

Discussion

The results of this investigation have shown that a maximal incremental exercise test followed by a period of light active recovery produces a reliable and reproducible estimate of IAT. Similar conclusions have been documented for an incremental test that ended when blood La values were close to 4 mmol$\cdot$l^{-1} (Jacobs et al. 1990) or for an incremental test to maximum followed by rest recovery (Orok et al. 1989). This latter study (Orok et al. 1989) also challenged the validity of the IAT but, for reasons that are not explained, exercised all subjects for up to 60 min at 40%, 60% and 80% $\dot{V}O_{2max}$ rather than at power outputs equivalent to, or slightly above or below individual estimates of IAT. For the present investigation, the validity of the determination of IAT was assessed on an individual basis.

The criteria used for the acceptance of a steady state response warrant some discussion. For *pH* and PCO_2, the criteria used were established from the precision of the calibration buffers and gas mixtures. Responses for PCO_2 followed the changes in *pH* such that if a steady-state response was observed for pH, a respiratory compensation was evident but PCO_2 values remained constant over the last 15 min of the test. As a result, the data were not presented for PCO_2. The criterion of a change in blood La of less than 0.5 mmol$\cdot$l^{-1} over a 15-min interval was somewhat arbitrary. Nevertheless, this rate of change of 0.03 mmol$\cdot$l$^{-1}\cdot$min^{-1} is small and less than the measurement error of 0.1 mmol$\cdot$l^{-1} for the YSI analyser. Similar rates of change in the blood La response have been used by others to define a steady state (Haverty et al. 1988; Mocellin et al. 1991). Finally, a total exercise time of at least 30 min was used to evaluate these steady-state criteria. Others have used an exercise time of approximately 60 min (Orok et al. 1989; Stegmann and Kindermann 1982) as an indication of an individual's ability to perform prolonged exercise. There is little doubt that any of the subjects in this study would have completed 60 min of exercise at their estimated IAT (see Fig. 3). However, for comparisons with our previous findings (Keith et al. 1992; McLellan et al. 1991; McLellan and Cheung 1992) we selected a 30-min evaluation period.

For the majority of subjects (i.e., 8 of 11), steady-state criteria for La and acidbase responses were observed at power outputs that were within 2.5% $\dot{V}O_{2max}$ of the estimated IAT. This range of variation is very close to the standard error of estimate for the protocol used to determine IAT. Therefore, these findings would imply that a valid estimate of IAT was obtained for these subjects using the exercise protocol that we recommended previously (McLellan et al. 1991). However, for the remaining subjects, there was an unacceptable difference between the true and the estimated IAT. An overestimation of IAT, as indicated by a failure to complete at least 30 min of exercise, has been observed in 11 of 91 evaluations at this laboratory (Keith et al. 1992; McLellan et al. 1991; McLellan and Cheung 1992). With the present data included, therefore, approximately 15% of our assessments have been associated with an invalid estimate of IAT.

What factors might account for the overestimation of IAT with this maximal incremental exercise test followed by a light active recovery period? The methods described by Stegmann et al. (1981) for the determination of IAT involve drawing a horizontal line from the end-of-exercise La curve to intersect the recovery La curve. A tangent from this point of intersection in recovery to the exercise curve defines the IAT. Clearly, when an overestimation of IAT is observed, the inter-

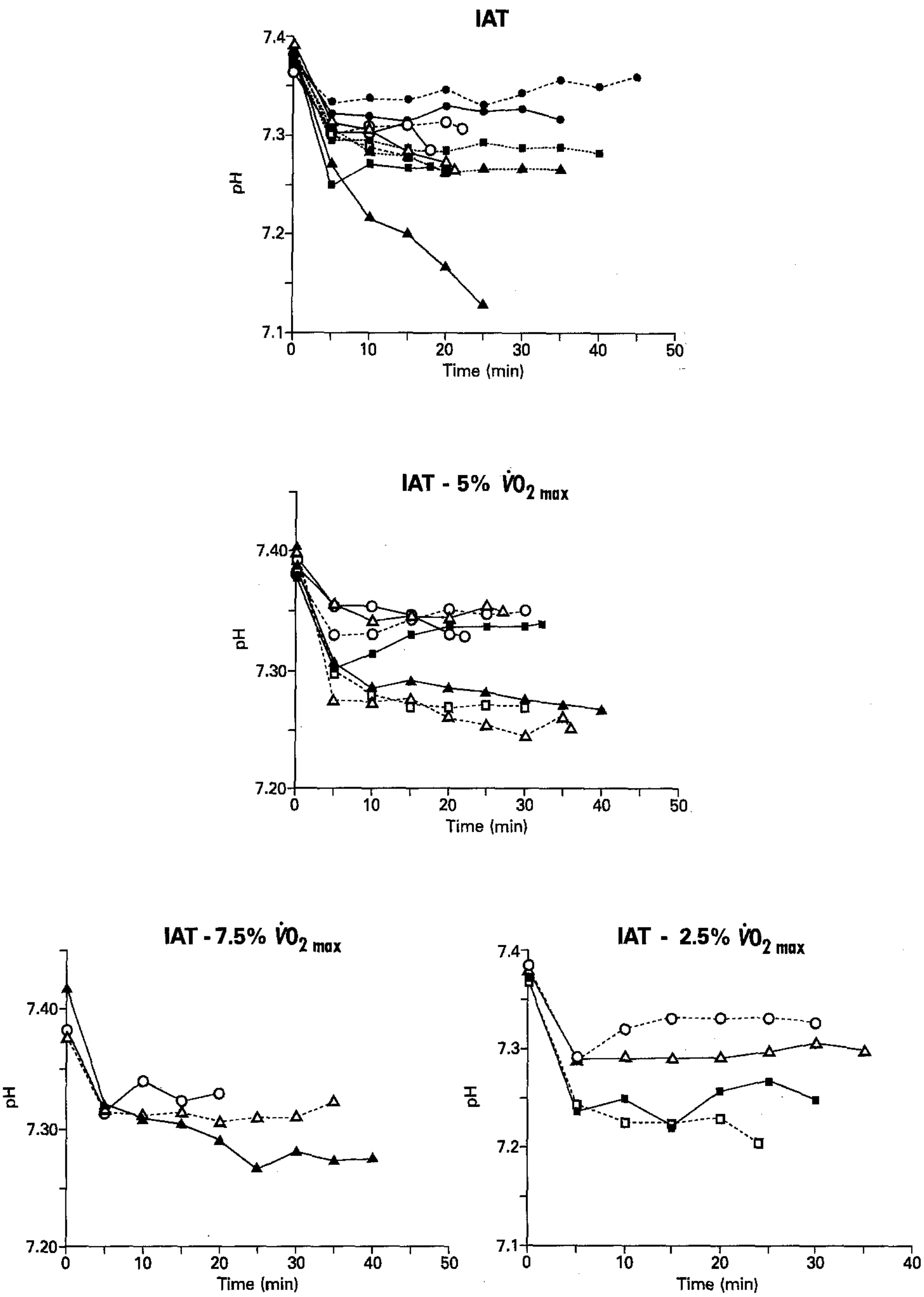

Fig. 6. Individual pH responses during the prolonged exercise test at the individual anaerobic threshold (IAT) for all 11 subjects and then for 7 individuals at −5% and either −7.5% or −2.5% $\dot{V}O_{2max}$ below IAT. For symbols see Fig. 3

section of the recovery curve by this horizontal line has occurred very early in the recovery period. The mathematical functions that we have used to describe the exercise (i.e., single exponential) and recovery (i.e. third-order polynomial) La curves have been associated with small error variances in all cases, and, thus, could not account for the overestimation. It is possible that our La values, which represent unlysed whole blood, are influenced by a reversal of the concentration gradient between the plasma and erythrocytes during the recovery period (Buono and Yeager 1986). If this occurred, the La concentrations would decrease rapidly and this would result in an overestimation of IAT. However, both Harris and Dudley (1989) and McKelvie et al. (1991) have reported that the La gradient between the plasma and erythrocyte is maintained during recovery from high-intensity exercise. Also, it should be remembered that light exercise, rather than rest, was used during the recovery period for the determination of IAT. Owing to the design of the present study, it cannot be discounted that some subjects experienced a systematic detraining effect over the course of the investigation. Maximal aerobic power was not measured at the end of the study to verify an unchanged fitness level. Finally, the different sites of blood sampling (i.e., ear versus hand) cannot explain the overestimation of IAT (see Table 1).

The mathematical model described by Stegmann et al. (1981) assumes that the increase in the rate of elimination of La above IAT is negligible compared with the increase in the rate of appearance of La during steady-state exercise. This assumption is not supported

Table 1. Blood lactate concentrations obtained from heating the earlobe or a dorsal hand vein at rest, during an incremental exercise test and during a recovery period with light activity

	Blood lactate concentration ($mmol \cdot l^{-1}$)	
	Earlobe	Hand
Rest	0.61 (0.21)	0.67 (0.18)
Exercise		
60 W	0.78 (0.29)	0.77 (0.29)
90 W	0.83 (0.36)	0.81 (0.37)
120 W	1.08 (0.65)	1.06 (0.59)
150 W	1.56 (0.98)	1.52 (0.93)
180 W	2.38 (1.58)	2.38 (1.64)
210 W	2.86 (1.02)	2.88 (0.96)
240 W	4.00 (1.25)	4.08 (1.16)
Recovery at 60 W		
1 min	4.63 (1.35)	4.71 (1.32)
2 min	4.50 (1.34)	4.54 (1.31)
5 min	3.68 (1.32)	3.69 (1.33)
8 min	2.84 (1.22)	2.79 (1.20)
10 min	2.38 (1.09)	2.28 (1.0)

Values are mean (SD). $N=6$ except for 210 W ($N=5$) and 240 W ($N=4$)

by tracer studies (MacRae et al. 1992; Mazzeo et al. 1986; Stanley et al. 1985) or a comparison of arterialised and venous blood sampling from the inactive forearm during leg exercise (Orok et al. 1989). It is unclear, therefore, exactly what is represented by the horizontal line drawn from the end-of-exercise La curve to the recovery curve with respect to the rate of elimination of La. The assumption that this point of intersection with the recovery La curve also represents a time when the elimination of La is maximal is not obvious. Nevertheless, for the majority of subjects, a valid estimate of IAT occurs using the methods described by Stegmann et al. (1981) and the incremental exercise protocol recommended previously (McLellan et al. 1991). The validity of all IAT determinations cannot be assumed, however, without verification.

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