JEPonline
Journal of Exercise Physiology**online**

Official Journal of The American Society of Exercise Physiologists (ASEP)

ISSN 1097-9751
An International Electronic Journal
Volume 7 Number 1 May 2004

Fitness and Training

EFFECTS OF HIGH-INTENSITY INTERVAL TRAINING ON THE ACCUMULATED OXYGEN DEFICIT OF ENDURANCE-TRAINED RUNNERS.

Bickham DC and Le Rossignol PF

School of Health Sciences, Deakin University, 221 Burwood Highway, Burwood, Australia, 3125.

ABSTRACT

EFFECTS OF HIGH-INTENSITY INTERVAL TRAINING ON THE ACCUMULATED OXYGEN DEFICIT OF ENDURANCE-TRAINED RUNNERS. **Bickham, D.C. and Le Rossignol, P.F. JEP**online 2004;7(1):40-47. The purpose of the present study was to assess the sensitivity of the Bickham et al. (1) accumulated oxygen deficit (AOD) protocol for measuring changes in anaerobic capacity in endurance-trained runners undertaking a 6 week high-intensity sprint training program. This protocol used four submaximal treadmill runs and a forced y-intercept to measure the VO_2-speed relationship and calculate AOD. Secondly, potential mechanisms that are likely to accompany changes in anaerobic capacity were investigated. Seven endurance-trained runners (mean ± S.D.; age 27.0 ± 6.9 yr, weight 77.1 ± 9.8 kg, VO_2max 60.1 ± 3.2 mL/kg/min) completed a VO_2max test, four submaximal runs and a single high-intensity exhaustive run, pre- and post-training. Training involved the completion of four sets of repeated near maximal (90-100% perceived maximum effort) sprints of 5-15 s duration (40 to 100 m), conducted 3 times/week for 6 weeks. The number of repetitions of each sprint distance increased within the range of 2 to 8 throughout the 6 weeks of training. There was no change in the AOD, VO_2max, ventilation threshold (VT), VO_2 kinetics or economy of running post-training. However, the mean aerobic component of the high-intensity test post-training increased by 5.4 %, which may have facilitated the 15.3% ($P<0.05$) increased time to exhaustion or vice-versa. It was concluded that the current AOD method was unable to detect the potential small changes in AOD facilitating the increased time to exhaustion reported for the high-intensity test.

Keywords: running, VO_2 kinetics, economy

INTRODUCTION

Anaerobic capacity is particularly important for mid-term exhaustive exercise performance, such as the 800 m run, where exhaustion/performance is determined to a large extent by the total anaerobic energy contribution (2). The accumulated oxygen deficit (AOD) is the preferred method for measuring anaerobic capacity during high-intensity exhaustive exercise (3). Bickham et al. (1) re-assessed the AOD method for running and developed a protocol with a high level of precision that only required four submaximal tests and a forced y-intercept. It is appropriate that this time efficient protocol is evaluated to determine if it is sensitive to changes in anaerobic capacity that result from the introduction of high-intensity intervals to the training of fit endurance athletes.

It has been demonstrated that 6 weeks of high-intensity training can increase AOD by 10% to 20% with running (4,5) and 28% with cycling (6). However, a limitation of the studies by Medbø and Burgers (4) and Tabata et al. (6) is that they used untrained or relatively unfit athletes and the improvements in AOD that they achieved cannot be generalized to highly trained endurance athletes. It is important to develop anaerobic capacity in mid-term endurance athletes as their lower anaerobic capacity (7) is likely to limit performance and there is little scope for aerobic improvements due to their already high level of endurance fitness (8). While it is known that these athletes can improve anaerobic capacity, it is not known if the AOD method is sensitive to training designed to improve the anaerobic capacity.

To date, the exact VO_2 mechanisms, like initial VO_2 kinetics, economy of VO_2 and the proportion of aerobic/anaerobic energy that underlie the changes in anaerobic capacity with a high-intensity training program are yet to be determined for endurance-trained subjects. High-intensity training can consist of short intervals with short recoveries or longer intervals with longer recoveries. It has been found that training involving short intervals (5-15 s) with short recoveries (1:3 work: recovery), as employed by Dawson et al. (9), can stimulate an increased anaerobic capacity as demonstrated by increases in supramaximal treadmill time. The first aim of this investigation was to assess the sensitivity of the Bickham et al. (1) AOD protocol to 6 weeks of high-intensity short interval running training. The second purpose was to investigate the underlying factors, such as submaximal VO_2 economy and VO_2 kinetics, that may account for the changes in AOD with high-intensity training in highly trained endurance athletes.

METHODS

Subjects

Seven endurance-trained male distance runners (mean ± S.D.; age 27.0 ± 6.9 yr, weight 77.1 ± 9.8 kg, VO_2max 60.1 ± 3.2 mL/kg/min) volunteered to take part in the study. Subjects were required to have a VO_2max greater than 55 mL/kg/min and to have completed a minimum of one year of endurance training. Prior to testing, written informed consent was obtained from all subjects, as approved by the Deakin University Human Research Ethics Committee. The subjects were asked not to participate in any excessive physical activity 24 hours prior to testing and to wear similar clothing/footwear for each session.

Test methods

All treadmill tests were performed on a motor driven treadmill (Quinton, Q65, Seattle WA) set at a grade of 1%. It has been found that a 1% treadmill grade most accurately reflects the energetic cost of over-ground running (10). Treadmill speed was measured and adjusted during the initial 5 s of each test with the use of a handheld tachometer (Emona Instruments, Australia). A Medical Graphics Corporation metabolic cart (Cardio2 and CPX/D system, St Paul MN) collected and analyzed expired gases breath by breath during the tests of VO_2max, submaximal intensity running and high-intensity exhaustive running. The metabolic cart was manually calibrated prior to each test using two alpha-rated gases (21% & 0.3%, 12% & 5%, O_2 & CO_2, respectively) with an error of 0.01%. To reduce increases in core temperature, oxygen drift and dehydration, the exercising environment was kept at 20?C with a fan directed at the subjects face and chest (1). Heart rates were continuously monitored using Polar Vantage heart rate monitors (NV, Finland). A warm-up consisting of 8 min at 167 m/min, with an increase to 233 m/min for two additional minutes, was completed by each subject at the start of every test session. The running warm-up was followed by an individual stretching routine. Subjects lowered themselves onto the moving treadmill at the start of each test using safety rails situated on each side of the treadmill (1).

Measurement of **VO_2*max***

Subjects were required to perform a continuous incremental treadmill test starting at 233 m/min with increases of 16.7 m/min every 2 min until volitional exhaustion (1). The subjects were given strong verbal encouragement throughout the test to elicit their best performance. The tests were terminated when the athlete placed their hands on the safety rail. Criteria for attainment of VO_2max were a plateau in VO_2, an RER above 1.1 or heart rate above 90% of age-predicted maximum. All subjects fulfilled a minimum of two of the above criteria. The ventilation threshold (VT) was considered to be equivalent to the second inflection point, defined as the upward deflection of both V_E/VO_2 and V_E/VCO_2 (11).

Establishing **VO_2*– speed relationships***

Subjects were required to complete four 4 min submaximal runs. The duration of 4 min for the submaximal tests was chosen as it has been suggested that this duration is sufficient to reach a steady state VO_2 below LT (12). Two intensities were selected below VT. The other two intensities included VT and the midpoint between VT and the velocity associated with VO_2max. The session consisted of four by 4 min submaximal exercise tests, randomly assigned, and separated by 20 min of recovery. Prior to each 4 min submaximal test, 1 min of "resting" data was collected with the subject in a straddled position on the treadmill.

Establishing the estimated total energy demand

The estimated total energy demand (ETED) required for the high-intensity test was forecast from the VO_2-speed linear regression. Two submaximal values below VT and two submaximal values at and above VT, with a forced individual y-intercept (resting VO_2values) were used in the regression. The ETED was calculated as the VO_2 at 110% velocity of VO_2max (1).

High-intensity exhaustive test

Subjects were required to complete a constant load high-intensity treadmill test, at 110% of the velocity eliciting VO_2max, until exhaustion (1). The test was terminated when the subject placed their hands on the safety rail. Due to the high running speeds of this test, a spotter was placed in a catching position behind the subject. The subjects were given strong verbal encouragement throughout the test to elicit their best performance.

Training

Subjects undertook three sessions a week of high-intensity interval training for a period of 6 weeks. The training program was adapted from Dawson et al. (9). On average each subject completed seventeen out of the eighteen training sessions. Each session comprised of four sets of repeated near maximal (90-100% perceived maximum effort) sprints of 5-15 s duration (Table 1). The number of sprints per session was increased during the 6-week period from an initial 14 repetitions to 30 repetitions. The length of individual repetitions was also increased throughout the 6-week period from an initial range of 40-80 m to 80-100 m. Finally, over the 6-week period the work to rest ratio of repetitions was decreased from an initial 1:5 to 1:4 to 1:3, with a familiarization of the new workload undertaken in the preceding week. The recovery between sets was maintained at 5 min throughout the training period. Subjects either walked or jogged during the recovery between repetitions or between sets. The sessions were completed on a grass oval under the supervision of the investigator.

Statistics

Data was analyzed in Stata 6.0 (Stata Corporation). A two-way ANOVA on economy calculated as VO_2 at 4 min divided by speed of running compared the four submaximal VO_2 tests both pre- and post-training. The slope of the individual submaximal VO_2-speed regressions were calculated via linear regression of 4 min VO_2's across the four individual speeds using an individual y-intercept. Paired sample t-tests compared the individual slopes, ETED and 95% confidence interval (CI) of ETED of the VO_2–speed regression at 4 min pre- and post-training. The ETED and 95% CI for ETED were calculated using standard linear prediction formulae. The AOD was calculated as the difference between the ETED for the high-intensity test and VO_2 measured during the test (3). Paired sample t-tests compared AOD and VO_2 max variables pre- and post-training. Potential changes in VO_2 kinetics using 10 s averaged data during the first 60 s of the high intensity test were assessed by a two-way ANOVA at six 10 s intervals pre- and post-training.

Table 1. Outline of the training program, showing the number of repetitions and distances covered for each session. The sets underlined were run at maximum effort.

Week	Session					% Max. effort	W:R	No. of reps.
1	1	4 x 40	4 x 50	4 x 60	2 x 80	90	1:5	14
	2	4 x 40	4 x 50	4 x 60	2 x 80	90	1:5	14
	3	4 x 40	4 x 50	4 x 60	4 x 80	90	1:5	16
2	4	6 x 40	4 x 50	4 x 60	2 x 80	90	1:5 (1:4)	16
	5	6 x 40	4 x 50	4 x 60	4 x 80	90	1:5 (1:4)	18
	6	6 x 40	6 x 40	4 x 60	4 x 80	90	1:5 (1:4)	20
3	7	6 x 40	6 x 40	6 x 80	4 x 80	90/100	1:4	22
	8	4 x 80	6 x 40	6 x 60	6 x 80	90	1:4	22
	9	8 x 40	6 x 40	6 x 80	4 x 60	90/100	1:4	24
4	10	8 x 60	6 x 60	6 x 80	4 x 80	90	1:4 (1:3)	24
	11	6 x 80	8 x 60	8 x 80	6 x 60	90/100	1:4 (1.3)	26
	12	8 x 80	6 x 40	8 x 80	4 x 40	90/100	1:4 (1:3)	26
5	13	8 x 40	8 x 80	8 x 80	4 x 100	90/100	1:3	28
	14	8 x 80	6 x 40	8 x 80	6 x 100	90/100	1:3	28
	15	6 x 100	8 x 80	4 x 100	8 x 60	90	1:3	26
6	16	8 x 100	8 x 60	8 x 80	6 x 80	90/100	1:3	30
	17	8 x 80	8 x 100	6 x 60	8 x 80	90/100	1:3	30
	18	8 x 100	6 x 100	8 x 80	6 x 80	90/100	1:3	28

W:R=work to rest ratio; 5 min recovery between sets; Adapted from Dawson et al. (9)

RESULTS

Data collected from the seven endurance-trained subjects pre- and post-training is shown in Table 2. Physiological variables of weight, VO_2max and VT remained unchanged ($P>0.05$) following the training period. There were no significant ($P>0.05$) differences in the slope and y-intercept of the linear regression pre- to post-training. There was a significant ($P<0.05$) increase of 15.3% in the time to exhaustion for the high intensity test post training (135.7 ± 13.6 s to 160.3 ± 10.5 s), which corresponded to 16.6 % increase in the distance covered (721.3 ± 62.2 m to 864.3 ± 55.7 m). There was no significant difference ($P<0.05$) in ETED pre- to post-training and the 6.2% increase in AOD post-training was not significant ($P>0.05$). However, the post training AOD for the same time interval as the pre training high intensity test was 3.7 % (not significant) lower with a 10% increase in AOD occurring during the additional 25 s of the post-training test.

Mean VO_2 data from the four by 4 min submaximal tests pre- and post-training are displayed in Figure 1a. There was no significant ($P>0.05$) difference for running economy over the four submaximal tests between pre- and post-training. Also there was no significant difference in the slope of VO_2-speed linear regression pre- to post-training (Table 2). Figure 1b is an example, from a representative individual, of the complete VO_2 response across the four submaximal tests pre-training.

Table 2. Group mean ± SD values for age, weight, VO_2max and ventilation threshold. Mean ± SE values for slope of linear regression of submaximal data, y-intercept for linear regression, time to completion of high-intensity test, distance covered in high-intensity test, estimated total energy demand (ETED) and accumulated oxygen deficit (AOD).

	Pre-training	*Post-training*
Age, y	27.0 ± 6.9	
Weight, kg	77.1 ± 9.8	77.3 ± 10.3
VO_2*max, mL/kg/min*	60.1 ± 3.2	60.3 ± 5.3
Ventilation threshold, m/min	257.1 ± 22.7	258.1 ± 24.3
Slope, mL/kg/m	0.1817 ± 0.0035	0.1814 ± 0.0035
y-intercept, mL/kg/min	6.4 ± 0.2	6.3 ± 0.2
High-intensity 110% test		
Time, s	135.7 ± 13.6	160.3 ± 10.5*
Distance, m	721.3 ± 62.2	864.3 ± 55.7*
ETED, mL O2 Eq/kg/min	65.0 ± 1.8	65.3 ± 2.4
AOD, mL O2 Eq/kg/min	48.1 ± 3.2	51.2 ± 3.4 (46.4 ± 3.4)

* P<0.05 between conditions; Data calculated with same pre-training time to exhaustion

a b

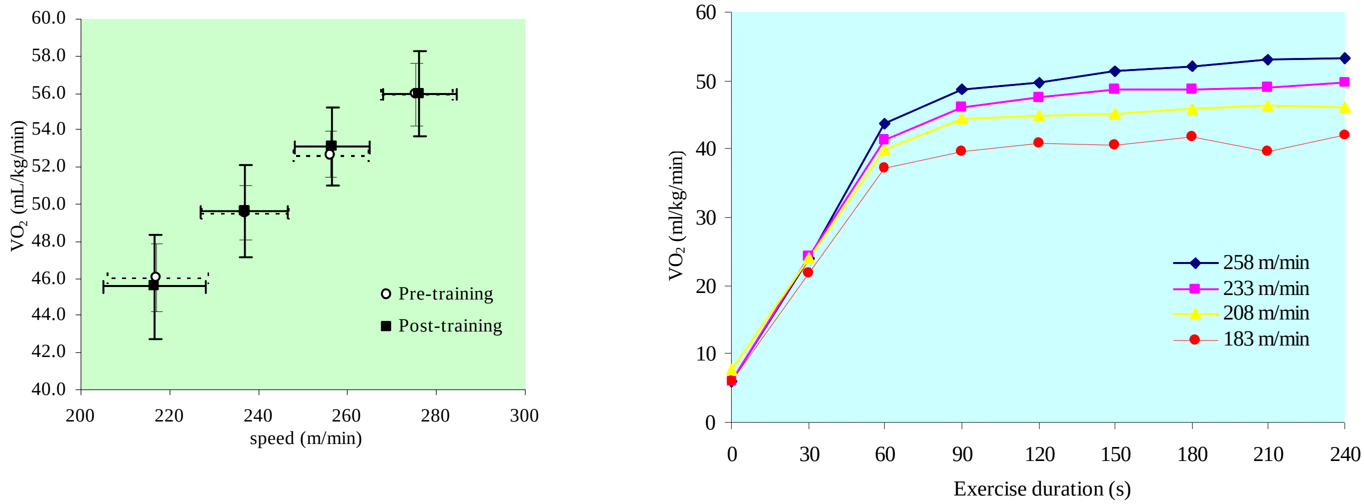

Figure 1. Submaximal VO_2 a) Group mean ± SE, pre- and post-training, and b) a representative individual data set for the 4 submaximal 4 min bouts.

The mean energy contribution of the high-intensity test, broken into total aerobic and anaerobic components, pre- and post-training is shown in Figure 2. There was a significant (P<0.01) increase in the total energy contribution to the high-intensity bout post-training, despite no change occurring in the anaerobic contribution to the task. The mean aerobic component of the high-intensity test increased (P<0.05) from 65.0% to 70.4% post-training.

Group mean results for VO_2 during the first minute of the high-intensity test are summarized for 10 s intervals pre- and post-training in Figure 3. There was no significant difference in VO_2 kinetics between pre- and post-training.

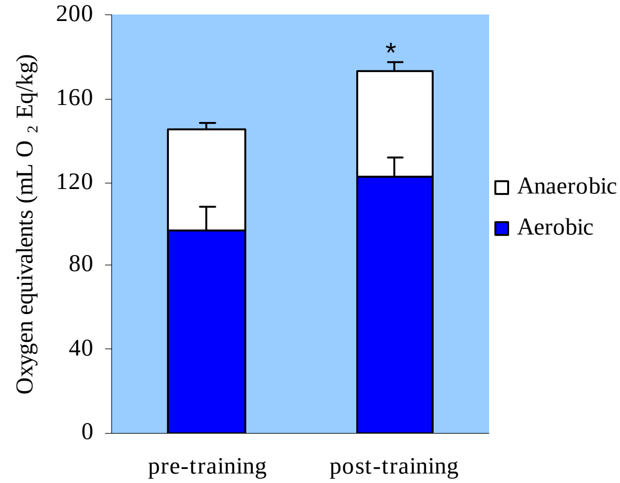

Figure 2. Comparison of the mean total energy contribution pre- and post-training. * P<0.05 between conditions.

DISCUSSION

Following 6 weeks of high-intensity interval training there were no significant changes in AOD or VO_2max in previously trained endurance runners. However, significant performance improvements occurred in the post-training test, including a 15.3% increase in time to exhaustion and a concurrent 16.6% increase in the distance covered during the high-intensity test. Post-training there was a larger total energy demand in the high-intensity test, which consisted primarily of a 5.4 % increase in the proportion of aerobic energy required for the task, in conjunction with a 25 s increased time to exhaustion.

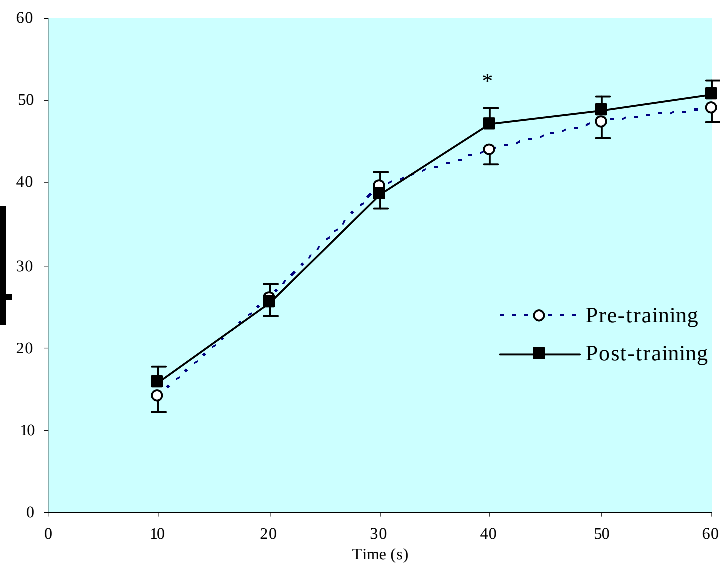

Figure 3. Group mean ± SE values for VO_2 every 10 s during the first minute of the high-intensity test at 110% velocity at VO_2max.

The main purpose of this study was to evaluate if a precise way of measuring AOD in running was sensitive to potential changes in anaerobic capacity in endurance trained runners. Post 6 weeks of high-intensity training there were no changes in VO_2max and the runners ran for 15% longer on the high-intensity test. This finding is supported by the data of Billat et al. (13), who demonstrated that significant adaptations and performance improvements not represented by VO_2max occurred in well-trained subjects after intense interval training. While there was no significant change in AOD in the present study, all but one of the subjects demonstrated an increase in AOD following 6 weeks of high-intensity interval training with an average group improvement of 3.1 mL/kg or 6.2%. This improvement is smaller than the 10 % increase in AOD detected by Medbo and Burgers (4) in untrained subjects. It is always easier to produce significant changes in untrained compared to trained individuals due to the law of diminishing returns. However, since the 95% CI for the calculation of ETED in the present study was found to be 5 mL/kg, changes of higher magnitude would be required to demonstrate a significant change in the AOD calculated from an ETED with this level of precision. This finding indicates that the Bickham et al. (1) AOD protocol lacks the precision required to demonstrate small but significant improvements in AOD which result from high-intensity interval training. However it is plausible that longer intervals in the vicinity of 20-40 s may be more effective at improving anaerobic capacity as measured by AOD than the shorter intervals employed in this study. Longer intervals (1-3 min) would tax the capacity of the phosphagen and glycolytic systems to a greater extent than shorter intervals.

The second aim of this study was to investigate potential mechanisms that are likely to be associated with improvements in anaerobic capacity and supramaximal performances in previously highly trained endurance runners. Figure 1a demonstrates that there appeared to be no changes in VO_2 over the four submaximal running speeds pre- to post–training. This observation was supported by the individually calculated running economy (VO_2/speed) with no significant changes occurring with 6 weeks of high-intensity training. Delta economy as demonstrated by the slope of the individual VO_2-speed regressions also remained unchanged with training. When VO_2 kinetics were investigated in the first sixty seconds of the high-intensity test it was found that there were no significant changes with 6 weeks of high-intensity training in the already trained endurance athletes. The appearance of an increase in VO_2 kinetics is typically observed at the completion of endurance training (14,15). Billat et al. (16) also demonstrated an increased rate of VO_2 kinetics after 4 weeks of high-intensity training, despite no change in VO_2max (58.1 mL/kg/min), in active but not endurance-trained subjects. Bishop et al. (17) has also demonstrated performance improvements in kayak paddlers without changes in AOD, attributable to an increased rate of VO_2 kinetics. This was mainly a result of a changed pacing strategy, which employed a very fast start, rather than a more even paced stroke rate. Despite the failure to observe significant changes in the above aerobic variables, there was a larger post-training total energy demand in the high-intensity test, which consisted primarily of a 5.4 % increase in the proportion of aerobic energy required for the task. This potentially indicates that some form of aerobic adaptation took place to account for the 15% increased time to exhaustion in the high intensity performance test. Also, when comparing the AOD at the same time to exhaustion pre- and post-training, similar to Weber et al. (18), there was a 3.7 % lower score in AOD, which did not reach significance. It is possible that lower levels of anaerobic metabolites were produced during the early stages of the high intensity test and this reduced fatigue. Consequently, subjects were able to continue for longer in the post-training high-intensity test.

CONCLUSIONS

Following 6 weeks of high-intensity interval training in endurance-trained athletes there was a 15.3 % increased time to exhaustion in the high-intensity test, which was facilitated without significant increases in VO_2max or AOD. Economy of running and VO_2 kinetics also did not change with 6 weeks of high-intensity training. However, post-training there was a larger total energy demand in the high-intensity test, which consisted primarily of a 5% increase in the proportion of aerobic energy required for the task. The Bickham et al. (1) AOD protocol for running lacked sensitivity for detecting the potentially small changes in the AOD that accompany high intensity interval training. Additional research is needed to improve our understanding of the mechanisms responsible for an increased aerobic contribution to intense exercise performance after high intensity interval training.

ACKNOWLEDGEMENTS

We thank Carl Gibbons for his statistical assistance and advice.

Address for correspondence: Dale C. Bickham, Biological Structure and Function Section, Division of Biomedical Sciences, Imperial College, South Kensington, London SW7 2AZ. E-mail: **d.bickham@imperial.ac.uk**

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