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Article *in* Medicine & Science in Sports & Exercise · March 1997

Impact Factor: 3.98 · DOI: 10.1097/00005768-199703000-00015 · Source: PubMed

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Wolters Kluwer Health | Lippincott Williams & Wilkins MEDICINE & SCIENCE IN SPORTS & EXERCISE® Official Journal of the American College of Sports Medicine

 Volume 29(3), March 1997, pp 390-395

Metabolic profile of high intensity intermittent exercises
[Applied Sciences: Physical Fitness and Performance]

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Submitted for publication January 1996.

Accepted for publication September 1996.

The authors appreciated stimulating discussions with Dr. Mitsumasa Miyashita (University of Tokyo) and the generous help of Ms. Donna Gardecki and Mr. Raymond Fujino in editing the English manuscript.

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ABSTRACT

To evaluate the magnitude of the stress on the aerobic and the anaerobic energy release systems during high intensity bicycle training, two commonly used protocols (IE1 and IE2) were examined during bicycling. IE1 consisted of one set of 6-7 bouts of 20-s exercise at an intensity of approximately 170% of the subject's maximal oxygen uptake ($\cdot VO_{2max}$) with a 10-s rest between each bout. IE2 involved one set of 4-5 bouts of 30-s exercise at an intensity of approximately 200% of the subject's $\cdot VO_{2max}$ and a 2-min rest between each bout. The accumulated oxygen deficit of IE1 (69± 8 ml·kg^{-1}, mean ± SD) was significantly higher than that of IE2 (46 ± 12 ml·kg^{-1}, N = 9, p< 0.01). The accumulated oxygen deficit of IE1 was not significantly different from the maximal accumulated oxygen deficit (the anaerobic capacity) of the subjects (69 ± 10 ml·kg^{-1}), whereas the corresponding value for IE2 was less than the subjects' maximal accumulated oxygen deficit (P < 0.01). The peak oxygen uptake during the last 10 s of the IE1 (55 ± 6 ml·kg^{-1}·min^{-1}) was not significantly less than the $\cdot VO_{2max}$ of the subjects (57± 6 ml·kg^{-1}·min^{-1}). The peak oxygen uptake during the last 10 s of IE2 (47 ± 8 ml·kg^{-1}·min^{-1}) was lower than the $\cdot VO_{2max}$ (P < 0.01). In conclusion, this study showed that intermittent exercise defined by the IE1 protocol may tax both the anaerobic and aerobic energy releasing systems almost maximally.

During high intensity exercise, ATP is resynthesized by both aerobic and anaerobic processes (17,18). The ability to resynthesize ATP may limit performance in many kinds of sports. Thus, the focus for training of athletes participating in sports involving high intensity exercise should be on improving the athletes' ability to release energy both aerobically and anaerobically. It is conceivable that the more demanding the training is the greater the fitness benefit will be. In this study we were interested in how commonly used specific exercises tax the anaerobic and aerobic energy release systems.

The aerobic energy release has traditionally been determined by measuring the oxygen uptake during exercise (1,8,10,12,13). By measuring the oxygen uptake and comparing that value with the subjects' maximal oxygen uptake ($\cdot VO_{2max}$), the stress on the aerobic energy release can be evaluated during training. The anaerobic energy release, depending on phosphocreatine breakdown and lactate production, is probably limited by lactate accumulation in the working muscles (18).

Until recently, methods for quantifying the anaerobic energy release have been inadequate, and therefore little information is available on the anaerobic energy release during exercise. We have proposed that the accumulated oxygen deficit, first introduced by Krogh and Lindhard (11), is an accurate measure of the anaerobic energy release during continuous exercise such as treadmill running (16,19) and bicycling (7,17). This principle may also allow quantification of the anaerobic energy release during high intensity exercises. Therefore, the metabolic profiles of high intensity exercise may also be evaluated by determining the accumulated oxygen deficit during high intensity exercises and comparing that entity with the subjects' anaerobic capacity (16,20).

Previously reported profiles of high intensity exercises were limited to exhausting continuous exercises (16,20). We have studied metabolic profiles of high-intensity intermittent exercises that have been used frequently as training exercise by top athletes involved in high intensity exercise lasting 1 min or less. Two different intermittent exercise protocols that are regularly used by coaches of top level Japanese speed skaters have been compared.

MATERIALS AND METHODS

Subjects. Nine young male students majoring in physical education volunteered for the study (Table 1). They were members of varsity tennis, baseball, basketball, football (soccer), or swimming teams. After receiving an explanation of the purposes, potential benefits, and risks associated with participating, the students gave their written consent.

N	Age (yr)	Height (cm)	Weight (kg)	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Anaerobic Capacity ($ml \cdot kg^{-1}$)
9	22 ± 1	171 ± 6	69.3 ± 4.5	57 ± 6	69 ± 9

Values are means ± SD. $\dot{V}O_{2max}$: the maximal oxygen uptake.
Anaerobic capacity: maximal accumulated oxygen deficit.

TABLE 1. Characteristics of the subjects.

The protocol for the experiment and the procedures involved were approved by the Ethics Committee at the National Institute of Fitness and Sports in Kanoya.

Protocol. All experiments as well as pretests were conducted on a mechanically braked cycle ergometer (Monark, Sweden) at 90 rpm. Each test was preceded by a 10-min warm-up at approximately 50% of the subject's·VO_{2max}.

Pretest. For each subject the oxygen uptake was measured during the last 2 min of six to nine different 10-min bouts of exercise at constant power. The power used during each bout ranged between 39 and 87% of the subject's ·VO_{2max}. In addition, the power required to exhaust each subject in 2-3 min was established. These pretests were carried out on 3-5 separate days.

Intermittent exercises. Two intermittent exercise protocols (IE1 and IE2) were compared in terms of aerobic and anaerobic energy release.

The protocol for IE1 was bouts of 20-s exercise carried out at an intensity of 170% of the subject's ·VO_{2max}. Each bout was separated by 10-s rest, and the procedure was repeated 6-7 times to exhaustion. The protocol for IE2 was bouts of 30-s exercise carried out at an intensity of 200% of the subject's ·VO_{2max}. Each bout was separated by 2 min of rest, and the procedure was repeated 4-5 times to exhaustion. For both protocols, the criterion for exhaustion was that the subjects were unable to maintain the pedaling frequency at or above 85 rpm near the end of the bout.

Expired gas was collected continuously every 10 s by Douglas bags during the exercise and rest periods to measure the oxygen uptake.

Methods

·VO2max. After a linear relationship between the exercise intensity and the steady-state oxygen uptake had been determined in the pretests, the oxygen uptake was measured for the last two or three 30-s intervals during several bouts of supramaximal intensity exercise that laster for 2-4 min. The highest $\cdot VO_2$ observed was taken as the subject's$\cdot VO_{2max}$ (22).

Anaerobic capacity. Anaerobic capacity, taken as the maximal accumulated oxygen deficit during 2-3 min of exhaustive bicycle exercise, was determined according to the method of Medbø et al.(16). The exercise intensity chosen to allow the subjects to reach exhaustion within the desired duration (2-3 min) was established on pretests. To determine the anaerobic capacity, the subjects exercised at the preset power to exhaustion.

Methods of analysis. Fractions of oxygen and carbon dioxide in the expired air were measured by a mass spectrometer (MGA-1100, Perkin-Elmer, Norwalk, CT). The gas volume was measured by a gasometer (Shinagawa Seisakusho, Shinagawa, Tokyo, Japan).

Calculations. For each subject linear relationships between the oxygen demand and power (r = 0.998 ± 0.001) were established from the measured steady-state oxygen uptake at different powers during the pretests. The Y-intercept, the slope, and the error of regression ($S_{y,x}$) were 6.0± 0.9 $ml\cdot kg^{-1}\cdot min^{-1}$, 218 ± 7$\mu l\cdot J^{-1}$, and 0.7 ± 0.1 $ml\cdot kg^{-1}\cdot min^{-1}$, respectively.

Accumulated oxygen deficit during 2-3 min of exhaustive exercise. The oxygen demand during the 2-3 min exhausting exercise was estimated by linear extrapolations of these relationships to the power used during the experiment. The accumulated oxygen demand was taken as the product of the estimated oxygen demand and the duration of the exercise, while the accumulated oxygen uptake was taken as the measured oxygen uptake integrated over the duration of exercise. The accumulated oxygen deficit was taken as the difference between these two entities.

Accumulated oxygen deficit during exhaustive intermittent exercise. For the intermittent exercise the oxygen demand during exercise was taken from the linear extrapolations of the oxygen demand versus power relationship established during the pretest (Fig. 1). The oxygen deficit during each bout of the exercise was taken as the difference between the oxygen demand and the oxygen uptake during the intermittent exercise. The excess post-exercise oxygen consumption (EPOC), which reflects a recovery of the body's oxygen stores and possibly some resynthesis of phosphocreatine during the rest periods, was calculated to be the difference between measured oxygen uptake during the rest periods and resting oxygen demand (2,3). The oxygen demand at rest between each bout of the exercise was set equal to the resting oxygen uptake measured before the experiment. Finally, the accumulated oxygen deficit during exhaustive intermittent exercise was calculated to be the difference between the sum of the oxygen deficit during each bout of the intermittent exercises and the sum of EPOC during the rest period between bouts of the intermittent exercise.

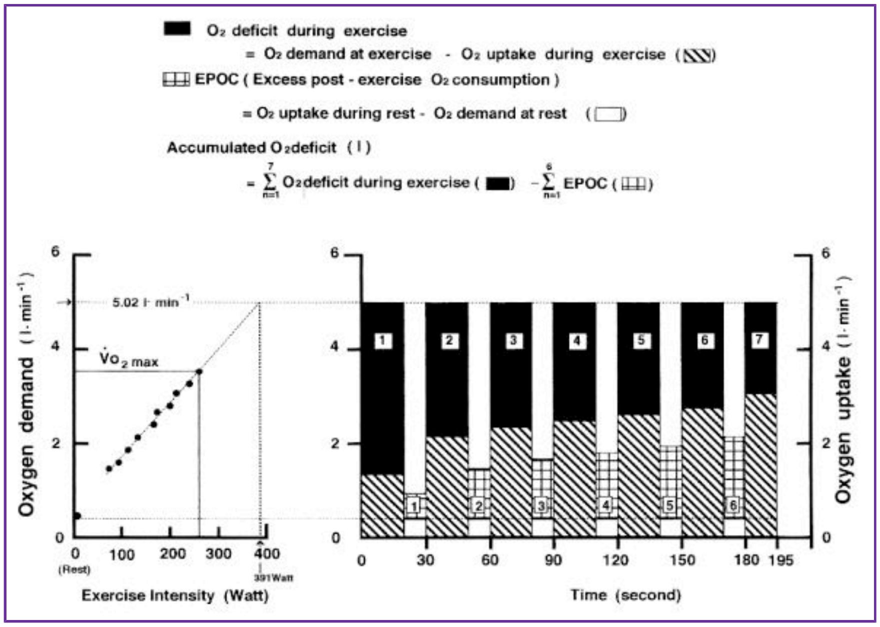

Figure 1-Principle of calculating the accumulated oxygen deficit for the high intensity intermittent exercise.

Statistics. Values are shown as means ± SD. The data were statistically analyzed using a repeated-measures one-way ANOVA to determine the degree of significance among the groups. The significance level for all comparisons was set at $P < 0.05$.

RESULTS

Six of the nine subjects completed the sixth bout of the exercise at the intensity of the subjects' 170% $\cdot VO_{2max}$ (IE1 protocol), while the other three subjects became exhausted during the seventh bout of the exercise. For the IE2 protocol, seven subjects completed the fourth bout of exercise at the intensity of the subject's 200% $\cdot VO_{2max}$, while the other two subjects became exhausted during the fifth set of the exercise. Total exercise time was not different between the two protocols (IE1:126 ± 6 s, IE2:126 ± 10 s). The total work output for IE1 (1.05 ± 0.16 kJ·kg^{-1}) was significantly less than that of IE2 (1.26 ± 0.15 kJ·kg^{-1}) ($P < 0.001$).

The accumulated oxygen deficit of IE1 was significantly higher than that of IE2 (69 ± 8 ml·kg^{-1} versus 46 ± 12 ml·kg^{-1}, respectively, $P < 0.01$)(Fig. 2). The accumulated oxygen deficit of IE1 was not significantly different from the anaerobic capacity of the subjects, whereas the accumulated oxygen deficit of IE2 was only 67% of the anaerobic capacity($P < 0.01$).

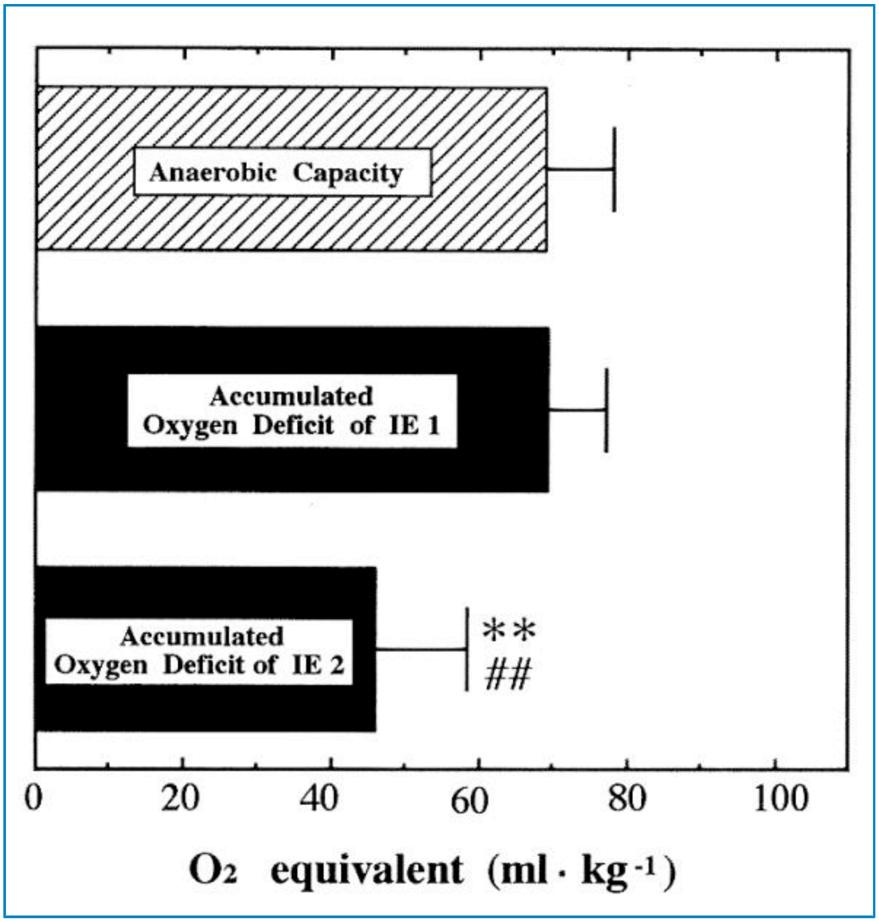

Figure 2-Accumulated oxygen deficit during the two intermittent exercises and the anaerobic capacity. **indicates a significant difference from the anaerobic capacity ($P < 0.01$). ## indicates a significant difference from the accumulated oxygen deficit of IE1($P < 0.01$).

The peak oxygen uptake during the last 10 s of the IE1 (55 ± 6 $ml \cdot kg^{-1} \cdot min^{-1}$) was not statistically different from the subjects' $\dot{V}O_{2max}$ (Fig. 3). On the other hand, the peak oxygen uptake of the last 10 s of IE2 (47 ± 8 $ml \cdot kg^{-1} \cdot min^{-1}$) was much less than the $\dot{V}O_{2max}$ ($P < 0.01$).

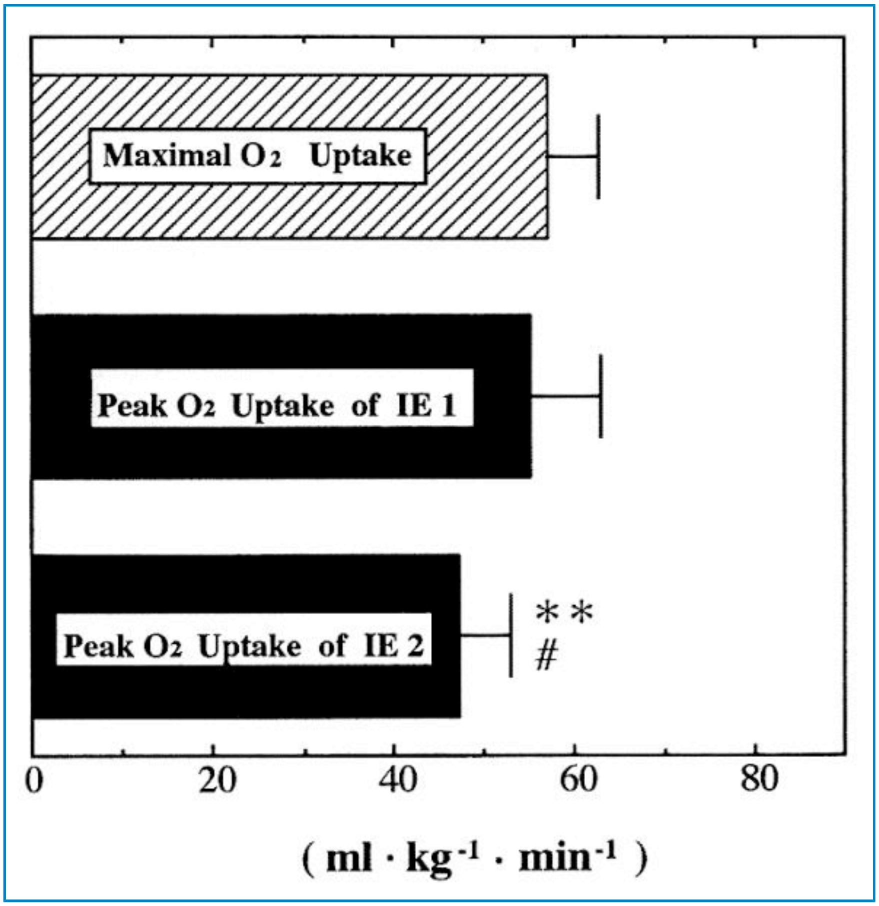

Figure 3-Peak oxygen uptake during the last 10 s of the two intermittent exercise bouts and the maximal oxygen uptake. **indicates a significant difference from the ·VO2max at*P* < 0.01. #indicates a significant difference from the peak oxygen uptake during IE1 exercise IE1 (*P* < 0.05).

DISCUSSION

The main finding of this study was that, of the two intermittent exercise protocols examined, both the accumulated oxygen deficit and the oxygen uptake were close to the maximum obtainable for IE1 but not for IE2.

We have shown that the accumulated oxygen deficit measures the anaerobic energy release during continuous high-intensity bicycling (17). To our knowledge, a corresponding approach has not been used until now for intermittent high-intensity bicycling. In the present study, the accumulated oxygen deficit for repeated bouts of exercise was calculated by assuming that in the recovery periods between each bout the oxygen uptake in excess of the resting value (EPOC (2,3)) is used for recovery of energy stores at a 1:1 ratio. This is likely to be correct for restoring the oxygen stores and for the resynthesis of phosphocreatine. First, near infrared spectroscopy study of HbO_2, a method of evaluating changes in oxygen level in tissue, showed that time constant of this measure calculated from the values obtained after exhausting exercise is approximately 30 s (14). Therefore, in IE2 the stores may have been fully replenished during each 2-min rest and that it is used over again during each of the exercise bouts thereafter. Consequently, repeated use of stored oxygen is important for the IE2 but not for the IE1. Second, Bogdanis et al.(4) showed that there was a significant phosphocreatine recovery within 2 min of rest. If the concentrations of phosphocreatine and ATP in muscle fluctuate by approximately 10 mmol·kg^{-1} wet muscle mass during each of the 30-s bouts of IT2, the phosphocreatine concentration may have nearly recovered to the pre-exercise value, while phosphocreatine in muscle may not have recovered fully during the 10-s rest in IE1 protocol. It should be noted that the calculation may not be correct if resynthesis of lactate to glycogen takes place during each rest period since this process takes 2-3 times more energy as ATP than what is released when glycogen is broken down to lactate. However, resynthesis of glycogen takes from many minutes to more than 1 h and is probably of little importance for a rest period lasting 10 s or 2 min. For example, Hermansen and Vaage (9), studying the recovery of muscle glycogen after exhausting bouts of exercise, found no resynthesis during the first 5 min of recovery. Therefore, calculating the accumulated oxygen deficit for repeated bouts of exercise as was done here should probably reflect the net anaerobic energy release during the intermittent bouts of high-intensity bicycling.

In this study we have used the accumulated oxygen deficit as a measure of the net anaerobic energy release during high intensity bicycling, and we have compared the entities obtained during different types of exercise. The reasoning behind our approach follows. During a 2-3 min exhausting bout of exercise, there is a breakdown of phosphocreatine and production of lactate, and exhaustion is probably reached when the muscle lactate concentration reaches about 30 $mmol\cdot kg^{-1}$ wet muscle mass (18,23). During intermittent exercise lactate is produced and phosphocreatine broken down during each bout. In the rest period, there is no further lactate production, but some phosphocreatine may be resynthesized by aerobic processes, at least during the 2-min rest period of IE2 (4). It is conceivable that as the muscle lactate concentration reaches a certain level the subjects are no longer able to exercise at the preset power and are thus exhausted. Interestingly, the accumulated oxygen deficit of IE1 equaled the subjects' accumulated maximal oxygen deficit. This observation may suggest that at exhaustion the muscle lactate concentration was as high as at the end of the 2-3 min exhausting bout.

As in the previous studies (16,17), the oxygen demand at a high power was extrapolated from a linear relationship between power and the steady-state oxygen uptake at moderate intensities. Recently, Zoladz et al. (24) reported nonlinear effects at high powers. However, as shown in Figure 1, our data clearly show that the steadystate oxygen uptake increased linearly by power within the range measured (39 and 87% of the subject's $\cdot VO_{2max}$). Therefore, it is probably reasonable to estimate energy demand at the high intensity from the regression line between power and oxygen uptake established at moderate intensities.

For most physical properties the more demanding the training is the greater the improvement of the property. Therefore, we were interested in how much the current training exercises stress the anaerobic and aerobic energy releasing systems by comparing accumulated oxygen deficit and oxygen uptake during the exercise to the anaerobic capacity and the $\cdot VO_{2max}$, respectively. The results from this investigation showed that the accumulated oxygen deficit during IE1 equaled the anaerobic capacity and thus seemed to stress the anaerobic energy system maximally. Furthermore, it recruited the oxygen delivery system almost maximally since the oxygen uptake measured during the last part of IE1 was not different from the $\cdot VO_{2max}$. On the other hand, neither the anaerobic nor aerobic systems seemed to be fully stressed during IE2. Therefore, for the purpose of improving both the anaerobic and aerobic energy releasing systems, IE1 seems superior to IE2.

We evaluated the two training protocols by comparing the net anaerobic energy release during the exercises. However, it may also be interesting to compare the total anaerobic energy release during the exercise because training effects may be dependent on the total anaerobic energy released during training. The calculated total oxygen deficit during exercise of IE2(154.4 ± 16.4 $ml\cdot kg^{-1}$ was greater than that of IE1 (99.5± 12.1 $ml\cdot kg^{-1}$) ($P < 0.001$). Therefore, in terms of total anaerobic energy release, IE2 seems more demanding than IE1. It could be argued that this view is very important when we consider metabolic profile of training. However, since Medbø and Burgers (15) showed that training with more oxygen deficit(their group A) was not more effective on the anaerobic capacity than the training with less oxygen deficit during training (their Group B), the total anaerobic energy released during training might not be a decisive factor to determine the effect of training on anaerobic capacity. Future training studies should be done to study whether the net oxygen deficit or the total anaerobic energy release during the training exercise is more effective factor than each other on anaerobic capacity.

High-intensity intermittent training has been shown to be a very effective means of increasing the maximal oxygen uptake (6). In line with this, we have recently shown that 6 wk of training using IE1 protocol may increase the maximal oxygen uptake by 13%(21). This increase is similar to that expected for intermittent training according to Fox (6). It is conceivable that it is not the exercise intensity *per se* but the high oxygen uptake that is usually found during high-intensity intermittent training that results in the improved maximal oxygen uptake. If this interpretation is correct, IE1 may be one of the best possible training protocols for improving the aerobic energy releasing system since the oxygen uptake reached the maximal value. On the other hand, IE2 does not seem to stress the oxygen delivery system maximally, and this protocol may therefore be less effective than IE1 for improving the maximal oxygen uptake. However, we are not aware of any study examining the actual effect of training according to this protocol on the maximal oxygen uptake.

Each bout during IE2 was carried out at a higher intensity and for a longer duration than the bouts in IE2. Therefore, it could be hypothesized that the oxygen uptake during IE2 should be at least as high as during IE1. However, during the relatively long rest periods of 2 min during IE2 the oxygen uptake fell considerably. At the onset of a new exercise bout there is a delay before the oxygen uptake increases and approaches the maximum.

Training effects may be dependent on the total work done during training. With this view, it could be hypothesized that IE2 might be more effective than IE1 because the total work done during IE2 protocol was greater than of IE1. However, since the improvement of $\cdot VO_{2max}$ after intermittent running training is related not to running distance but to exercise intensity (5), it may be reasonable to assume that the high oxygen uptake obtained during some kinds of intermittent training leads to the significant stress on the aerobic system and results in the large increase in the maximal oxygen uptake.

On the other hand, since the moderate intensity endurance training, during which much more work is done in one training session than in a session following either IE1 or IE2 protocol, has no influence on the anaerobic capacity (21), the total work *per se* may not be an important parameter that predicts improvement of the anaerobic system after specific training regimens.

Many commonly used training regimens are based on little scientific evidence. We have, therefore, examined two different intermittent exercise protocols from the viewpoints of maximal aerobic power and the accumulated oxygen deficit. Our data suggest that one protocol seems superior to the other since IE1 appears to stress both the aerobic and anaerobic energy releasing systems maximally, while IE2 did not. It may therefore recommend that protocol IE1 is used rather than IE2. Our approach may be used for evaluating other training.

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ACCUMULATED OXYGEN DEFICIT; ANAEROBIC CAPACITY; MAXIMAL OXYGEN UPTAKE; BICYCLING

Accession Number: 00005768-199703000-00015