Eur J Appl Physiol (2000) 81: 188–196

ORIGINAL ARTICLE

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Intermittent runs at the velocity associated with maximal oxygen uptake enables subjects to remain at maximal oxygen uptake for a longer time than intense but submaximal runs

Accepted: 27 July 1999

Abstract Interval training consisting of brief high intensity repetitive runs (30 s) alternating with periods of complete rest (30 s) has been reported to be efficient in improving maximal oxygen uptake ($\dot{V}O_{2\,max}$) and to be tolerated well even by untrained persons. However, these studies have not investigated the effects of the time spent at $\dot{V}O_{2\,max}$ which could be an indicator of the benefit of training. It has been reported that periods of continuous running at a velocity intermediate between that of the lactate threshold (v_{LT}) and that associated with $\dot{V}O_{2\,max}$ ($v_{\dot{V}O_{2\,max}}$) can allow subjects to reach $\dot{V}O_{2\,max}$ due to an additional slow component of oxygen uptake. Therefore, the purpose of this study was to compare the times spent at $\dot{V}O_{2\,max}$ during an interval training programme and during continuous strenuous runs. Eight long-distance runners took part in three maximal tests on a synthetic track (400 m) whilst breathing through a portable, telemetric metabolic analyser: they comprised firstly, an incremental test which determined v_{LT}, $\dot{V}O_{2\,max}$ [59.8 (SD 5.4) ml · min^{-1} · kg^{-1}], $v_{\dot{V}O_{2\,max}}$ [18.5 (SD 1.2) km · h^{-1}], secondly, an interval training protocol consisting of alternately running at 100% and at 50% of $v_{\dot{V}O_{2\,max}}$ (30 s each); and thirdly, a continuous high intensity run at v_{LT} + 50% of the difference between v_{LT} and $v_{\dot{V}O_{2\,max}}$ [i.e. $v_{\Delta 50}$: 16.9 (SD 1.00) km · h^{-1} and 91.3 (SD 1.6)% $v_{\dot{V}O_{2\,max}}$]. The first and third tests were performed in random order and at 2-day intervals. In each case the subjects warmed-up for 15 min at 50% of $v_{\dot{V}O_{2\,max}}$. The results showed that in more than half of the cases the $v_{\Delta 50}$ run allowed the subjects to reach $\dot{V}O_{2\,max}$, but the time spent specifically at $\dot{V}O_{2\,max}$ was much less than that during the alternating low/high intensity exercise protocol [2 min 42 s (SD 3 min 09 s) for $v_{\Delta 50}$ run vs 7 min 51 s (SD 6 min 38 s) in 19 (SD 5) interval runs]. The blood lactate responses were less pronounced in the interval runs than for the $v_{\Delta 50}$ runs, but not significantly so [6.8 (SD 2.2) mmol · l^{-1} vs 7.5 (SD 2.1) mmol · l^{-1}]. These results do not allow us to speculate as to the chronic effects of these two types of training at $\dot{V}O_{2\,max}$.

Key words Intermittent exercise · Running · Training · Oxygen consumption

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Introduction

Interval training was first described by Reindell and Roskamm (1959) and Reindell et al. (1962), and was popularised in the 1950s by the Olympic champion, Emil Zatopek. Middle and long-distance runners have since used it to train at running velocities close to their own competition velocities. Daniels et al. (1984) have defined the parameter $v_{\dot{V}O_{2\,max}}$ as the velocity (v) associated with maximal oxygen uptake ($\dot{V}O_{2\,max}$) determined by an incremental exercise test on a treadmill. Furthermore, this $v_{\dot{V}O_{2\,max}}$ has been found to be close to the average velocity maintained over 3 000 m (Daniels et al. 1984; Padilla et al. 1992; Lacour et al. 1991). Within the same group of researchers, Gorostiag et al. (1991) have shown that interval training with repetitions of 30-s exercise at 100% $v_{\dot{V}O_{2\,max}}$, separated by 30-s rest, produced larger increases in $\dot{V}O_{2\,max}$ than did continuous training at 50% $v_{\dot{V}O_{2\,max}}$. Both this continuous training or the intermittent style only elicited an oxygen uptake ($\dot{V}O_2$) of 70% of $\dot{V}O_{2\,max}$. In addition to the above studies, it has been accepted for a long time that a typical endurance type training programme would consist of repeated 1–8 min runs at 90%–100% $v_{\dot{V}O_{2\,max}}$ (Fox 1975). All of these studies have aimed to improve $\dot{V}O_{2\,max}$ and have been based on the assumption that the more specific the stimulus, (i.e. taxing the cardiovascular and aerobic enzyme systems to their maximum) the greater the improvement. However, none of these studies have examined the effect of the time the athlete spent at $\dot{V}O_{2\max}$.

It is of note therefore that in none of the work cited was it checked to see if the subjects reached $\dot{V}O_{2\max}$ during the interval training sessions. However, Astrand et al. (1960) have reported that interval training of 30-s runs at $v_{\dot{V}O_{2\max}}$ alternating with rest of the same duration elicited a $\dot{V}O_2$ equal to 65% of $\dot{V}O_{2\max}$ accompanied by a very low blood lactate concentration (2.2 mmol $\cdot$ l^{-1}). Astrand et al. (1960) have also reported that interval training using shorter repetitions (15 s at $v_{\dot{V}O_{2\max}}$ alternating with 15 s of complete rest) was similarly incapable of bringing $\dot{V}O_2$ to the maximal level.

However, it has been suggested that continuous running above the running velocity at which the critical velocity (CV) is attained (Moritani et al. 1981) could be more efficient at maintaining a metabolic rate closer to $\dot{V}O_{2\max}$ than interval training at $v_{\dot{V}O_{2\max}}$ and thus elicit a more pronounced training stimulus. Indeed, it has now been recognised that continuous running, at an appropriate velocity, causes runners to reach $\dot{V}O_{2\max}$ (Gaesser and Poole 1996).

Indeed, previous studies have reported that in "severe exercise" an additional slow phase of increase in $\dot{V}O_2$ (the $\dot{V}O_2$ slow component) is superimposed upon the underlying $\dot{V}O_2$ kinetics and $\dot{V}O_2$ continues to rise until the end of the test or until exhaustion, and will eventually drive $\dot{V}O_2$ to the $\dot{V}O_{2\max}$ (Poole et al. 1988; Whipp 1994). Therefore, using this $\dot{V}O_2$ slow component, it might be possible to elicit $\dot{V}O_{2\max}$ for an extended period, provided that the subjects run for a sufficiently long period at this supra-CV.

We are not aware of any published work which compares the training effect of time spent at $\dot{V}O_{2\max}$ during interval training with the time spent at $\dot{V}O_{2\max}$ during a strenuous continuous run which elicits $\dot{V}O_{2\max}$ using the slow component phenomenon. Therefore, the purpose of this study was to compare the time spent running at $\dot{V}O_{2\max}$ in a commonly used interval training protocol (30s at $v_{\dot{V}O_{2\max}}$—30s at 50% of $v_{\dot{V}O_{2\max}}$) with that achieved during a run at a continuous supra-CV ($v_{\Delta 50}$). We speculated that this could be a method for eliciting $\dot{V}O_{2\max}$ at a slower running velocity.

We hypothesised that running at $v_{\Delta 50}$ would allow subjects to remain closer to $\dot{V}O_{2\max}$ for a longer period than intermittent running at $v_{\dot{V}O_{2\max}}$ whilst eliciting a similar accumulation of lactate in the blood.

Methods

Subjects

Eight endurance trained male athletes [mean age 34 (SD 6) years, mean height 175.0 (SD 5) cm and mean bodymass 69 (SD 4) kg] volunteered to participate in this study. They trained four times a week [mean 60 (SD 16) km $\cdot$ week^{-1}] with continuous running below or at their lactate threshold (LT; i.e. 50%–80% $v_{\dot{V}O_{2\max}}$) but were unfamiliar with either severe intermittent or continuous runs. Prior to participation, all the subjects provided voluntary written informed consent in accordance with the guidelines of the University of Lille.

Experiment design

The subjects took part in three all-out tests. They did only one test on any given day and tests were each separated by 48 h or more, but all were completed within a week. All the tests took place on a synthetic 400-m track at the same time of day (between 10 h AM and 16 h PM) in an ambient temperature of 19–22°C without winds. The subjects were required to be rested when they reported to the track and not to train hard (easy jogging of 40 min only on the day separating any two tests). They were asked to refrain from consuming food or beverages containing caffeine before the test. On the track runners followed a pacing cyclist travelling at the required velocity. The cyclist received audio cues via a Walkman (Sony), the cue rhythm determining the sped needed to cover 50 m. Visual marks were set at 50-m intervals along the track (inside the first lane).

The first test was incremental for the determination of $\dot{V}O_{2\max}$, $v_{\dot{V}O_{2\max}}$ and the running velocity at the lactate threshold (v_{LT}) making it possible to calculate mid-point velocity between v_{LT} and $v_{\dot{V}O_{2\max}}$ ($v_{\Delta 50}$).

After this preliminary test the runners trained in random order, using two types of exercise until they were exhausted: (1) continuous running at $v_{\Delta 50}$, (2) intermittent runs of 30-s duration alternating between 100% and 50% $v_{\dot{V}O_{2\max}}$. Both of these types of training were preceded by 15 min of warming-up at 50% $v_{\dot{V}O_{2\max}}$.

Data collection procedures

Protocol of $\dot{V}O_{2max}$ and $v_{\dot{V}O_{2max}}$ determination

The initial velocity was set at 10 km $\cdot$ h^{-1} and increased by 1 km $\cdot$ h^{-1} every 2 min. Each stage was followed by a 30-s rest when a capillary blood sample was obtained from the finger tip to be analysed for lactate concentration (YSI 27, Ohio, Ill.). Measurement of $\dot{V}O_2$ was carried out throughout each test using a telemetric system (Cosmed K4b^2, Rom, Italy; Hausswirth et al. 1997; McLaughlin et al. 1999). Expired gases were measured breath-by-breath and averaged every 15 s. Before each test, the O_2 analysis system was calibrated using ambient air, the O_2 concentration of which was assumed to be 20.9%, and a gas of known CO_2 concentration 5% (K4 instruction manual). The calibration of the turbine flowmeter of the K4 was performed with a 3-l syringe (Quinton Instruments, Seattle, Wash., USA). The $\dot{V}O_{2\max}$ was defined as the highest $\dot{V}O_2$ attained in two successive 15 s. In this incremental protocol, $v_{\dot{V}O_{2\max}}$ was defined as the lowest running velocity maintained for more than 1 min which elicited $\dot{V}O_{2\max}$ (Billat and Koralsztein 1996). If an athlete achieved $\dot{V}O_{2\max}$ during a stage that was not maintained for 1 min, the speed during the previous stage was recorded as $v_{\dot{V}O_{2\max}}$. If the velocity at fatigue was only maintained for 1 min (half of the stage duration), then $v_{\dot{V}O_{2\max}}$ was considered to be equal to the velocity during the previous stage plus half the velocity increase between the last two stages, i.e. 1 km $\cdot$ h^{-1}/2 = 0.5 km $\cdot$ h^{-1} (Kuipers et al. 1985).

In this study, LT was defined as the $\dot{V}O_2$ corresponding to the starting point of an accelerated accumulation of lactate in the blood at around 4 mmol $\cdot$ l^{-1} and expressed as % $\dot{V}O_{2\max}$ (Aunola and Rusko 1984). Although the step-like increase in exercise intensity does not allow precise determination of the blood LT, the incremental test provides a useful index to delineate the level at which lactate starts to accumulate in the blood. This "threshold" is in accordance with that proposed by Aunola and Rusko (1984) which is closer to the onset of blood lactate accumulation defined by Sjödin and Jacobs (1981), rather than LT of Farrel et al. (1979) or LT determined by gas exchange (Wasserman et al. 1994).

Intermittent exercise

The intermittent training session consisted of alternating 30-s runs at 100% and 50% of if $v_{\dot{V}O_{2\,max}}$. For instance, a runner who had a $v_{\dot{V}O_{2\,max}}$ equal to 20 km · h^{-1} (5.55 m · s^{-1}) was required to cover 166 m in the first 30 s and half of this distance in the following 30 s. Blood samples for lactate determination were collected after the warm-up, at the 3rd, 6th and last minute of the protocol. At the 3rd min the samples were taken after 30 s at 50% $v_{\dot{V}O_{2\,max}}$ with the subject at rest for 10 s, and at the last minute the samples were taken after 30 s of jogging at $v_{\dot{V}O_{2\,max}}$.

Constant run at $v_{\Delta 50}$

After the warm-up the runners had to maintain their $v_{\Delta 50}$ (about 90% $v_{\dot{V}O_{2\,max}}$ in these subjects) as long as possible until they were exhausted.

For each of these two tests, time spent at $\dot{V}O_{2\,max}$ was determined from the time during which $\dot{V}O_2$ was at least equal to $\dot{V}O_{2\,max}$ minus 2.1 ml · min^{-1} · kg^{-1}. This criterion has been used by Taylor et al. (1955) to determine $\dot{V}O_{2\,max}$ in an incremental test. The $\dot{V}O_{2\,max}$ determined in the incremental test was compared with peak $\dot{V}O_2$ reached in the continuous test (time limit test).

The highest 15-s value for $\dot{V}O_2$ was recorded as $\dot{V}O_{2\,max}$; values for heart rate (f_c) from the 15-s period when $\dot{V}O_{2\,max}$ was reached were recorded as the maximal values for these variables. Blood samples for lactate determination were collected after the warming-up, and at 1 and 3 min after the onset of the exercise. The highest of these values was taken as the maximal blood lactate concentration for this all-out run at $v_{\Delta 50}$.

Data analyses

A one-way analysis of variance for repeated measurements and located by Scheffé's post-hoc tests was used to compare f_c, blood lactate concentration and $\dot{V}O_2$ between the incremental test and the two training procedures. Student's *t*-test, for paired data, was used to compare time to exhaustion at $\dot{V}O_{2\,max}$ in the constant and intermittent runs. Simple-wise regression was used to examine the relationship between the times specifically spent at $\dot{V}O_{2\,max}$ during the two training protocols. The correlation test of Pearson was used to correlate the two times spent at $\dot{V}O_{2\,max}$ in the two training protocols. Statistical significance was set at $P < 0.05$.

Results

Incremental test

The data obtained from individuals in the incremental test are presented in Table 1. It is salient to not that the subjects had a low maximal aerobic power [$\dot{V}O_{2\,max}$ 59.8 (SD 5.4) ml · min^{-1} · kg^{-1}, $v_{\dot{V}O_{2\,max}}$ 18.5 (SD 1.2) km · h^{-1}] and a high relative velocity at LT [82.5 (SD 2.6)% $v_{\dot{V}O_{2\,max}}$, 15.2 (SD 0.9) km · h^{-1}], in accordance with their type of training (slow short distance). Hence their $v_{\Delta 50}$ was set at a high percentage of $v_{\dot{V}O_{2\,max}}$ [91.3 (SD 1.6)% of $v_{\dot{V}O_{2\,max}}$, 16.9 (SD 1.0) km · h^{-1}]. Therefore, the difference in absolute velocity between $v_{\Delta 50}$ and $v_{\dot{V}O_{2\,max}}$ was 1.6 km · h^{-1}.

Continuous run at $v_{\Delta 50}$

Figure 1 shows the time course of $\dot{V}O_2$ for the intermittent exercise with the responses for the continuous running sessions superimposed.

Table 2 summarises the responses of f_c, $\dot{V}O_2$, and blood lactate concentration and time to exhaustion during $v_{\Delta 50}$ all-out run. The subjects maintained the required velocity for 8 min 20 s (SD 1 min 45 s). Seven runners out of the eight developed a $\dot{V}O_2$ slow component [$\Delta\dot{V}O_2 > 150$ ml · min^{-1} between the 3rd and the 6th min of exercise – average = 291 (SD 153) ml · min^{-1}].

Five runners out of the eight reached their $\dot{V}O_{2\,max}$ and they maintained it for an average of 4 min 51 s (SD 1 min 30 s) which for these runners was equivalent to 63 (SD 10)% of total time to exhaustion at this $v_{\Delta 50}$. During this $v_{\Delta 50}$ all-out run, f_c reached an average of 96% of the maximal f_c obtained in the incremental test.

Table 1 Data obtained from individual subjects in the incremental test. $v_{\dot{V}O_{2\,max}}$ Velocity associated with $\dot{V}O_{2\,max}$, $\dot{V}O_{2\,max}$ maximal oxygen uptake, f_c heart rate, v_{LT} velocity of lactate threshold

Subjects	$v_{\dot{V}O_{2\,max}}$ (km · h^{-1})	$\dot{V}O_{2\,max}$ (ml · min^{-1} · kg^{-1}) (ml · min^{-1})	$f_{c\,max}$ (beats · min^{-1})	Blood lactate (mmol · l^{-1})	v_{LT} (km · h^{-1})	v_{LT} (% $v\dot{V}O_{2\,max}$)	f_c at v_{LT} (beats · min^{-1})
1	20.0	66.7 3868	184	13.0	16.0	80.0	173
2	18.0	58.7 3874	183	8.8	15.0	83.3	170
3	19.0	62.7 4263	179	8.4	16.0	84.2	160
4	20.0	63.6 4324	182	10.0	16.0	80.0	165
5	18.0	59.3 4921	183	9.2	15.0	83.3	175
6	18.0	61.4 4052	208	8.9	14.0	77.7	190
7	16.5	48.7 3506	176	11.4	14.0	84.8	167
8	18.5	57.1 4282	203	9.1	16.0	86.5	190
Mean	18.5	59.8	188	9.9	15.2	82.5	174
SD	1.2	5.4	12	1.6	0.9	2.9	11

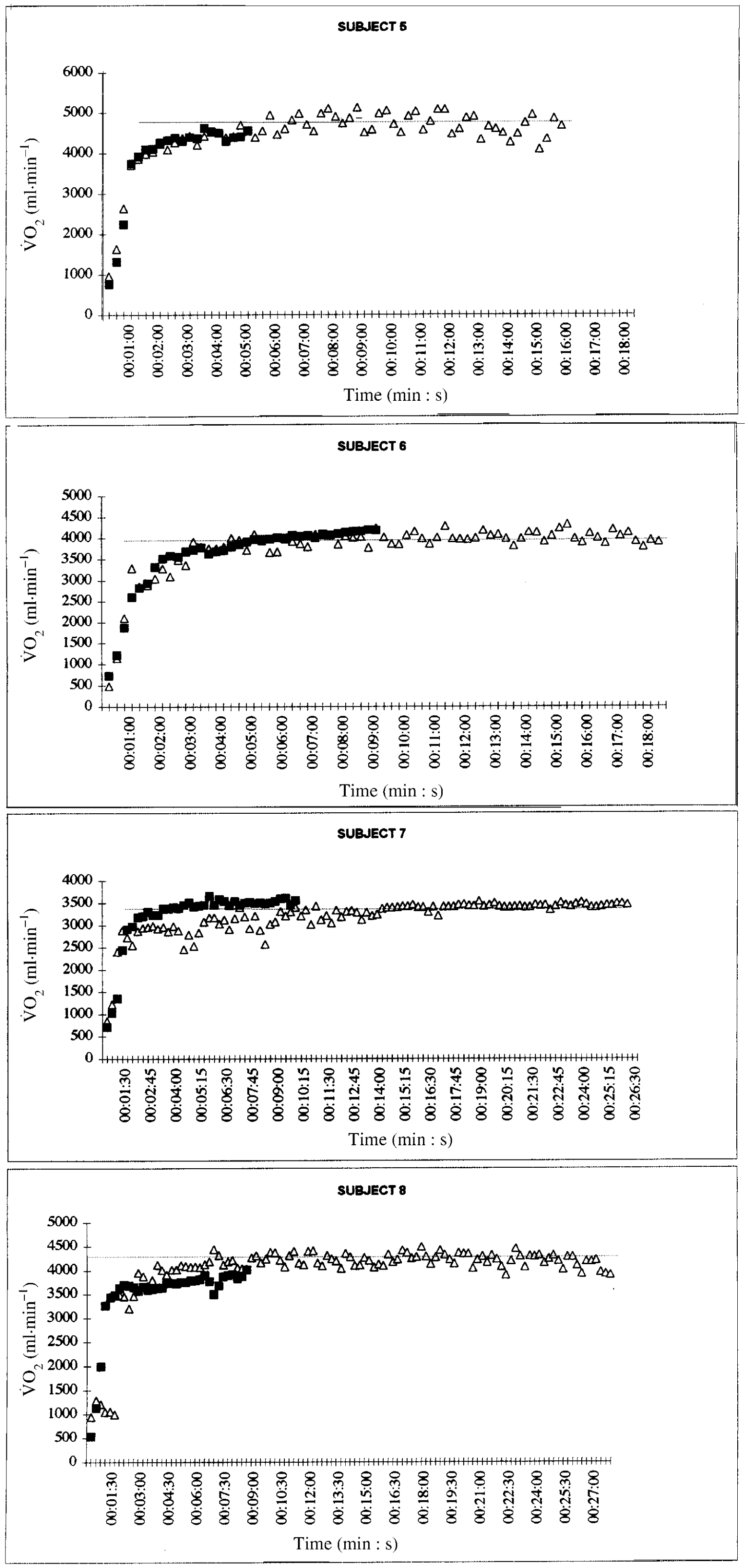

Fig. 1 Time course of oxygen consumption ($\dot{V}O_2$) during $v_{\Delta 50}$ (*filled symbols*) and intermittent exercise (*unfilled symbols*). The $v_{\Delta 50}$ was a running velocity midway between those at which the lactate threshold and maximal oxygen uptake occurred

Intermittent run at $v_{\dot{V}O_{2\max}}$

Table 3 summarises continuous effects of the intermittent run on the responses of f_c, $\dot{V}O_2$, blood lactate concentration and the time to reach exhaustion. The f_c reached 99% of the maximal f_c obtained in the incremental test. Blood lactate concentration was lower for this intermittent training run than for the $v_{\Delta 50}$ run, but

Table 2 Data obtained from individual subjects during $v_{\Delta50}$ all-out runs. $v_{\Delta50}$ Mid-point velocity between v_{LT} and $v_{\dot{V}O_{2max}}$, t_{lim} time limit. For other definitions see Table 1

Subjects	$v_{\Delta50}$ (km · h^{-1})	$\dot{V}O_{2max}$ (ml · min^{-1} · kg^{-1})	$\dot{V}O_{2max}$ (% $\dot{V}O_{2max}$ incremental test)	Maximal blood lactate (mmol · l^{-1})	$\Delta\dot{V}O_2$ 6–3 min (ml · min^{-1})	t_{lim} at $v_{\Delta50}$ (min:s)	t_{lim} at $\dot{V}O_{2max}$ (min:s)
1	18.0	62.8	94	9.0	127	6:59	0:00
2	16.5	61.4	104	9.7	412	8:04	3:00
3	17.5	59.0	94	7.0	263	8:22	0:00
4	18.0	67.0	106	8.2	576	10:48	7:00
5	16.5	55.6	94	8.2	161	5:04	0:00
6	16.0	63.5	103	6.7	275	9:00	4:00
7	15.0	50.8	104	8.7	358	9:49	5:45
8	17.3	53.0	93	6.4	158	8:30	4:30
Mean	16.9	60.9	99	8.0	291	8:20	2:42
SD	1.0	5.7	3	1.2	153	1:45	3:09

Table 3 Individual data in the intermittent run: 30 s at $v_{\dot{V}O_{2max}}$ alternated with 30 s at 50% of $v_{\dot{V}O_{2max}}$ until exhaustion. For other definitions see Tables 1 and 2

Subjects	$\dot{V}O_{2max}$ (ml · min^{-1} · kg^{-1})	$\dot{V}O_{2max}$ (% $\dot{V}O_{2max}$ incremental test)	f_{cmax} (beats · min^{-1})	f_{cmax} (% f_{cmax} incremental test)	Maximal blood lactate (mmol · l^{-1})	Distance in 30 s at $v_{\dot{V}O_{2max}}$	Number of intervals of severe exercise	t_{lim} at $\dot{V}O_{2max}$ (min:s)
1	68.0	102	186	101	10.2	166.7	22	14:15
2	61.3	104	182	99	5.9	150.0	14	4:00
3	58.8	94	179	100	7.3	158.3	12	0:00
4	63.6	100	183	101	9.4	166.7	16	0:30
5	61.6	104	182	97	5.6	150.0	16	4:45
6	65.4	107	208	100	8.0	150.0	18	10:45
7	49.2	101	177	101	7.8	137.5	25	11:15
8	57.0	100	195	96	5.2	154.2	27	18:30
Mean	61.1	102	186	99	7.4	154.3	19	7:51
SD	6.5	4	10	2	1.8	9.7	6	6:38

the difference was not significant [6.8 (SD 2.2) vs 7.5 (SD 2.1) mmol · l^{-1}, respectively, $P = 0.7$]. On average, the subjects maintained this interval training procedure for 19 (SD 5) repetitions, which represents 9.5 min (SD 2) min of severe exercise at $v_{\dot{V}O_{2max}}$. On average, from the fifth repetition until the end of intermittent training the $\dot{V}O_2$ elicited was not significantly different from $\dot{V}O_{2max}$ ($P = 0.62$). Furthermore, the $\dot{V}O_2$ did not vary significantly ($P = 0.56$) between each 30 s of high and low intensity exercise. Likewise, f_c did not vary significantly during the intermittent training session ($P = 0.51$). The $\dot{V}O_{2max}$ and maximal f_c values are not significantly different from the maximal values found in the incremental test (see Table 1; $P = 0.21$ and $P = 0.34$ for $\dot{V}O_{2max}$ and maximal f_c, respectively).

Maximal blood lactate concentrations for intermittent exercise and $v_{\Delta50}$ continuous run were significantly lower than those measured at the end of the incremental test ($P = 0.03$, $P = 0.05$, respectively) and were not significantly different from each other ($P = 0.4$).

Seven out of the eight runners reached their $\dot{V}O_{2max}$ and they maintained if for 7 min 51 s (SD 6 min 38 s) during the intermittent run. For these seven subjects, time run at $\dot{V}O_{2max}$ represented 83 (SD 45)% of cumulative time maintained at $v_{\dot{V}O_{2max}}$.

Total time run at $\dot{V}O_{2max}$ was related to the number of intervals run at $v_{\dot{V}O_{2max}}$ (n) during intermittent training ($r = 0.90$, $P = 0.02$) as follows:-

Total time at $\dot{V}O_{2max}$ (seconds)
$= n$ intervals $\times$ 64.8 −752.6

Discussion

The purpose of this study was to compare the time spent running at $\dot{V}O_{2max}$ during the interval training commonly used by runners (30-s at $v_{\dot{V}O_{2max}}$ followed by 30-s at 50% $v_{\dot{V}O_{2max}}$), with time spent at $\dot{V}O_{2max}$ during a strenuous continuous run in which $\dot{V}O_2$ slow component could appear. This last type of exercise has not yet been as a method of training used at $\dot{V}O_{2max}$ as trainers and athlete are uninformed about the $\dot{V}O_2$ slow component phenomenon. We wanted to ascertain whether this type of exercise would allow subjects to maintain $\dot{V}O_{2max}$ for a duration comparable with that of interval training, with the aim of devising a new training regime.

The contribution made by the present study is that we have shown that intermittent exercise (of 30 s at $v_{\dot{V}O_{2max}}$ alternated with 30-s run at 50% of $v_{\dot{V}O_{2max}}$) allowed subjects to maintain $\dot{V}O_{2max}$ for longer than continuous slower running (8 min vs 3 min), and that this occurred without a large accumulation of lactate in the blood. In fact, the main difference between the two types of training was the time spent at $\dot{V}O_{2\,max}$ which was 8 min for the intermittent modality (83% of total time run at $v_{\dot{V}O_{2\,max}}$) and 2 min 42 s for the continuous exercise session (about 50% of total time maintained at $v_{\Delta 50}$).

This study demonstrated that although both continuous strenuous runs and interval training (using short repetitions with active pauses) allowed subjects to reach $\dot{V}O_{2\,max}$, this very high metabolic rate was maintained for longer with the intermittent runs. Blood lactate concentration end values averaged 7.4 (SD 1.8) mmol $\cdot$ l^{-1} and 8.0 (SD 1.2) mmol $\cdot$ l^{-1} in interval and continuous training, respectively, and were not significantly different from each other, but these were both significantly below the value obtained at the end of the incremental test [9.4 (SD 1.9) mmol $\cdot$ l^{-1}]. Below we shall consider the effectiveness of both training regimes from the perspective of $\dot{V}O_2$ stimulation, the time spent at $\dot{V}O_{2\,max}$ and the accumulation of lactate in the blood.

Time spent at $\dot{V}O_{2\,max}$ during interval training

To *calibrate* the intensity of interval training, coaches often refer to the running velocity associated with the achievement of $\dot{V}O_{2\,max}$ during an incremental treadmill test ($v_{\dot{V}O_{2\,max}}$) and to the running velocity at the onset of accumulation of lactate in the blood. These have both been reported to be relevant indicators of performance for middle and long-distance running events (Sjödin and Jacobs 1981; Daniels et al. 1984; Lacour et al. 1991; Anderson 1994; Billat 1996; Billat and Koralsztein 1996). Optimal improvement in cardio-respiratory fitness has been thought to occur from training at an intensity corresponding to 90%–100% of $\dot{V}O_{2\,max}$ (Robinson et al. 1991). In fact, for the purpose of maximally taxing the oxygen-transport system, Astrand and Rodahl (1986) have recommended running for 10-s runs with 5-s pauses to reach $\dot{V}O_{2\,max}$. A well-trained athlete ($\dot{V}O_{2\,max}$ = 5.3 l $\cdot$ min^{-1}) was able to maintain this configuration of exercise for 30 min with an effective time run at $v_{\dot{V}O_{2\,max}}$ of 20 min (since rest:work ratio was 1:2; Astrand and Rodahl 1986). The oxygen deficit (difference between oxygen needed at this high velocity, i.e. $\dot{V}O_{2\,max}$ and oxygen actually consumed), has been suggested to be accounted for by using other energy stores such as high-energy phosphates (e.g. phosphocreatine) and the oxygen bound to myoglobin.

The duration of intermittent effort investigated in the literature varies considerably amongst authors. In training for track and field, intervals from 10 s to 3 min, generally separated by inactive rest, have been investigated but have not been referenced to individual capabilities to maintain high intensity exercise (i.e. time to exhaustion at $v_{\dot{V}O_{2\,max}}$; Billat and Koralsztein 1996). It has been shown that training with intermittent runs at 60% and 100% of $v_{\dot{V}O_{2\,max}}$ (of duration equal to half of the individual's time to exhaustion at $v_{\dot{V}O_{2\,max}}$) allowed long-distance runners to double the distance covered at $v_{\dot{V}O_{2\,max}}$ compared to continuous training runs at $v_{\dot{V}O_{2\,max}}$ (Billat et al. 1996). More recently, Billat et al. (1999a) and Smith et al. (1999) have reported that only one session per week (for 4 weeks) of this kind of individualised interval training duration (50%–75% of the time to exhaustion $v_{\dot{V}O_{2\,max}}$) significantly increased $v_{\dot{V}O_{2\,max}}$ in a group of middle and long-distance runners.

It seems surprising therefore, that longitudinal studies investigating different kinds of continuous or interval training around $v_{\dot{V}O_{2\,max}}$ have not examined the effective time run at $\dot{V}O_{2\,max}$ in their search for the most efficient training for improving $\dot{V}O_{2\,max}$ and $v_{\dot{V}O_{2\,max}}$. In fact, it is likely that these studies have assumed that time spent at $\dot{V}O_{2\,max}$ is closely related with time run at $v_{\dot{V}O_{2\,max}}$. We have shown that this assumption is valid for the intermittent exercise regime used in this study (seven subjects reaching $\dot{V}O_{2\,max}$ during this type of exercise). There was a tendency for this assumption to be valid during the continuous strenuous runs; only five of the eight subjects reached their $\dot{V}O_{2\,max}$ in this type of exercise.

Blood lactate accumulation in interval training

We saw that five subjects reached $\dot{V}O_{2\,max}$ in the intermittent exercise, and that the associated blood lactate concentration was at a steady-state and below 4 mmol $\cdot$ l^{-1} from the 3rd to the 6th min. Hence, for at least 1 min, these five runners were at $\dot{V}O_{2\,max}$ with only 4 mmol $\cdot$ l^{-1} of lactate in the blood. This is interesting as a previous study examining the accumulation of lactate in the blood during intermittent exercise have reported that only a high value of blood lactate accompanies a $\dot{V}O_2$ value at its maximum (Astrand et al. 1960). This was due to the fact that these studies employed long intervals of 2–3 min to elicit $\dot{V}O_{2\,max}$ (because they used complete rest between repetitions). Therefore, when using the 30-s rest/exercise intervals with an inactive pause they did not reach $\dot{V}O_{2\,max}$.

It has been reported that interval training at running velocities around $v_{\dot{V}O_{2\,max}}$ may maximise the improvement in $\dot{V}O_{2\,max}$, as well as result in significant improvements in mitochondrial density (Brooks et al. 1996). In fact, it has also been reported that in addition to these aerobic (O_2 transport) training benefits, interval training stimulates the rate of lactate removal which depends directly on its concentration (i.e. the greater the concentration, the greater the removal; Brooks et al. 1996). Therefore interval training that increases blood lactate concentrations will also stimulate improvement in lactate removal. For this reason Brooks et al. (1996) have recommended activity during the rest interval to stimulate this lactate removal and hence avoid blood lactate accumulation. Newsholme (1986) has found that despite high lactate production at these high velocities (i.e. above LT) walking or jogging in the rest phase of intermittent exercise would tend to stimulate oxidative recovery. Therefore, we suggest that active, rather than passive, pauses between the hard work intervals will not only elicit and maintain $\dot{V}O_{2\,max}$, but also stimulate lactate removal whilst remaining close to maximal blood lactate steady-state.

The blood lactate concentrations obtained at the end of the intermittent tests [6.8 (SEM 2.2) mmol · l^{-1}] were of similar magnitude to those reported by Gimenez et al. (1982), who used a 45-min exhausting "square wave" endurance exercise test composed of nine repetitions of 1 min at $v_{\dot{V}O_{2\,max}}$ and 4 min at 50% $v_{\dot{V}O_{2\,max}}$. This blood lactate concentrations were also in accordance with those reported by Billat et al. (1996) during running in interval training at $v_{\dot{V}O_{2\,max}}$ (length of intervals set at 50% of the individuals time to exhaustion at $v_{\dot{V}O_{2\,max}}$) separated by active pauses of the same duration run at a half velocity (50% $v_{\dot{V}O_{2\,max}}$). Saltin and Essen (1971) have found similar blood lactate concentrations at the end of 30 min of intermittent cycling with intervals of 30-s of supra-maximal exercise (400 W, % $\dot{V}O_{2\,max}$ not specified) and 60-s rest. Using the same ratio (1:2) between rest and exercise but doubling the length of each period (i.e. 60-s exercise and 120-s rest), their subjects tripled their end blood lactate concentrations (18 mmol · l^{-1}).

Continuous run at $v_{\Delta 50}$

The $\dot{V}O_2$ slow component phenomenon should have allowed the subjects to reach $\dot{V}O_{2\,max}$ by running at high, but sub-maximal, velocities (on the condition that it was continued until the subject was exhausted). We wanted to compare, therefore, the simple procedure currently used by trainers and athletes (30 s-30 s exercise-rest at 100% and 50% of $v_{\dot{V}O_{2\,max}}$) with a single continuous run at an intensity sufficient to reach $\dot{V}O_{2\,max}$.

In the present study, the exercise intensity chosen for the test was well above each athlete's LT, and was midway between the exercise intensities associated with LT and $\dot{V}O_{2\,max}$. In fact five runners out of the eight reached their $\dot{V}O_{2\,max}$ in this high constant velocity run.

This study showed that in a group of runners having a high fractional $\dot{V}O_{2\,max}$ at LT but not a very high $\dot{V}O_{2\,max}$, six out of the eight developed a $\dot{V}O_2$ slow component during track running at $v_{\Delta 50}$. That was not found to be the case in a study of high level runners having a similar endurance capacity (i.e. v_{LT} of 84% of $v_{\dot{V}O_{2\,max}}$) but with a $\dot{V}O_{2\,max}$ of 23% greater (75 ml · min^{-1} · kg^{-1} compared to 61 ml · min^{-1} · kg^{-1}; Billat et al. 1998). Indeed recently Billat et al. (1998) have reported that in a supra-critical velocity run (90% $v_{\dot{V}O_{2\,max}}$; Moritani et al. 1981), fourteen highly trained long-distance runners reached a steady-state $\dot{V}O_2$, but did not reach their $\dot{V}O_{2\,max}$ [$\dot{V}O_{2\,max}$ reached = 69.5 (SD 5.0) vs $\dot{V}O_{2\,max}$ of 74.9 (SD 3.0) ml · kg^{-1} · min^{-1}]. In other words highly trained long-distance runners did not exhibit the $\dot{V}O_2$ slow component when performing exhausting, supra-CV runs at 90% $v_{\dot{V}O_{2\,max}}$ significantly above their CV and v_{LT} (at 82% and 86% of $v_{\dot{V}O_{2\,max}}$, respectively). Instead, these runners maintained a steady-state $\dot{V}O_2$ below $\dot{V}O_{2\,max}$, such that the time to exhaustion at 90% of $v_{\dot{V}O_{2\,max}}$ for these runners was positively correlated with the CV expressed as percentage of $v_{\dot{V}O_{2\,max}}$. The CV has been found to correspond to an exercise intensity which lies between that associated with the LT and $\dot{V}O_{2\,max}$ (Billat et al. 1999b). It has been suggested that this intensity is comparable to that achieved in a competitive 10-km race (Poole et al. 1998; McLellan and Cheung 1992). Moreover, Gaesser and Poole (1996) have proposed that during prolonged exercise at intensities above CV, $\dot{V}O_2$ would continue to rise until $\dot{V}O_{2\,max}$ is reached. However, the result of the study of Billat et al. (1998) have reported that a $\dot{V}O_2$ slow component was not expressed by high level long-distance runners during exhausting supra-critical velocity runs at 90% of $v_{\dot{V}O_{2\,max}}$. Indeed, although these runners were assigned to run at an exercise intensity which was 5% above their CV (90% of $v_{\dot{V}O_{2\,max}}$), they reached a steady-state $\dot{V}O_2$ at an average of 93% of $\dot{V}O_{2\,max}$ for 17 min and did not demonstrate a progressive increase in $\dot{V}O_2$ with time. At the end of this all-out run they had a blood lactate concentration of 6.5 mmol · l^{-1}, a value of the same magnitude as those obtained in the present study.

This study would confirm that the $\dot{V}O_2$ slow component appears in subjects having a smaller $\dot{V}O_{2\,max}$ than that found in elite athletes. Previously most investigations have described the time course of $\dot{V}O_2$ during intense cycling exercise by untrained subjects (Roston et al. 1987; Poole et al. 1988; Henson et al. 1989). Thus, the absence of a significant $\dot{V}O_2$ slow component in the study of Billat et al. (1998) may be linked to the high-level of training of their subjects (Gerbino et al. 1996). Since an increase in the level of endurance training has been shown to reduce the magnitude of the $\dot{V}O_2$ slow component (Casaburi et al. 1987), we suggest that continuous high intensity exercise (i.e. $v_{\Delta 50}$) cannot be used to stimulate $\dot{V}O_{2\,max}$ in runners who have already a $\dot{V}O_{2\,max}$ greater than 65 ml · min^{-1} · kg^{-1}. However, we recall that three runners did not express a $\dot{V}O_2$ slow component and yet reached their $\dot{V}O_{2\,max}$ in less than 3 min.

Brooks et al. (1966) have compared the metabolic and performance responses of laboratory animals to endurance (5 days a week for 10 weeks comprising 2 h training periods at about 50% of $v_{\dot{V}O_{2\,max}}$) and sprint training (4-week daily programme of daily treadmill running for 1 and 2 min at about 130% of $v_{\dot{V}O_{2\,max}}$; Davies et al. 1981, 1982). These studies have shown that although sprint training increased $\dot{V}O_{2\,max}$, in a similar proportion to the endurance training (+15% and +14%, respectively) the improvement in endurance capacity (time to exhaustion at about 50% of $v_{\dot{V}O_{2\,max}}$) was only improved (+403%) after endurance training (Davies et al. 1981). After sprint training, the improvement of endurance capacity and the underlying metabolic adaptations were insignificant when compared to the adaptations to endurance training. However, if we consider the endurance (time to exhaustion) at $\dot{V}O_{2\,max}$, it could be interesting to compare the influence of training using protocols eliciting $\dot{V}O_{2\,max}$ but run at different velocities ($v_{\Delta 50}$ vs $v_{\dot{V}O_{2\,max}}$ for instance). Moreover, in accordance with Noakes (1991), the benefits of training have also been shown to depend on the distance covered at high velocity which determines the muscle adaptation in maximising the number of powerful muscle contractions. Our intermittent exercise at $v_{\dot{V}O_{2\,max}}$, not only allowed stimulation for a longer time of cardiovascular function at its maximum (at $\dot{V}O_{2\,max}$), but was run at higher velocity ($+1.6\ km \cdot h^{-1}$). Therefore, from the cardiovascular and muscle adaptation point of view, intermittent exercise at $v_{\dot{V}O_{2\,max}}$ would be likely to produce an increase in performance at middle-distances.

Conclusion

Before speculating on the cause of the improvement in $\dot{V}O_{2\,max}$ brought about by a given training design, it is necessary to examine the effect of this stimulus on cardiovascular and metabolic responses. In the absence of this information, we would suggest that the benefit of these training procedures on aerobic capacity (and especially on $\dot{V}O_{2\,max}$) is dependent on the time spent at $\dot{V}O_{2\,max}$ and also on the distance run at high velocity. With this in mind it is possible to discriminate between the benefits gained from interval or constant intensity regimes.

The results showed that even if a $v_{\Delta 50}$ run caused the subjects to reach $v_{\dot{V}O_{2\,max}}$ (which was the case in five out of the eight subjects), the time spent at $\dot{V}O_{2\,max}$ was much less than during the 30 s low-30 s high intensity exercise intervals. Moreover, the blood lactate response was less pronounced in the interval training than for the $v_{\Delta 50}$ run, but not significantly. Whereas these results do not allow us to speculate on the chronic effects of these two types of training at $\dot{V}O_{2\,max}$, at present the interval style of training is likely to be more beneficial. Further studies are necessary to elucidate whether these findings were specific to the trained state of this group.

Acknowledgement This study was supported by grants from la Caisse Centrale des Activités Sociales d'Electricité et Gaz de France.

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