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ORIGINAL ARTICLE

Influence of recovery mode (passive vs. active) on time spent at maximal oxygen uptake during an intermittent session in young and endurance-trained athletes

Delphine Thevenet · Magaly Tardieu-Berger · Serge Berthoin · Jacques Prioux

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Abstract The aim of this study was to analyze the effects of recovery mode (active/passive) on time spent at high percentage of maximal oxygen uptake (VO_{2max}), i.e. above 90% of VO_{2max} ($t90VO_{2max}$) and above 95% of VO_{2max} ($t95VO_{2max}$) during a single short intermittent session. Eight endurance-trained male adolescents (15.9 ± 1.4 years) performed three field tests until exhaustion: a graded test to determine their VO_{2max} (57.4 ± 6.1 ml min^{-1} kg^{-1}), and maximal aerobic velocity (MAV; 17.9 ± 0.4 km h^{-1}), and in a random order, two intermittent exercises consisting of repeated 30 s runs at 105% of MAV alternated with 30 s passive (IE_P) or active recovery (IE_A, 50% of MAV). Time to exhaustion (t_{lim}) was significantly longer for IE_P than for IE_A (2145 ± 829 vs. 1072 ± 388 s, $P < 0.01$). No difference was found in $t90VO_{2max}$ and $t95VO_{2max}$ between IE_P (548 ± 499–316 ± 360 s) and IE_A (746 ± 417–459 ± 332 s). However, when expressed as a percentage of t_{lim}, $t90VO_{2max}$ and $t95VO_{2max}$ were significantly longer ($P < 0.001$ and $P < 0.05$, respectively) during IE_A (67.7 ± 19%–42.1 ± 27%) than during IE_P (24.2 ± 19%–13.8 ± 15%). Our results demonstrated no influence of recovery mode on absolute $t90VO_{2max}$ or $t95VO_{2max}$ mean values despite significantly longer t_{lim} values for IE_P than for IE_A. In conclusion, passive recovery allows a longer running time (t_{lim}) for a similar time spent at a high percentage of VO_{2max}.

Keywords Intermittent exercise · Recovery mode · Time spent at maximal oxygen uptake · Time to exhaustion · Young athlete

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Introduction

Maximal oxygen uptake ($\dot{V}O_{2max}$) is the main variable used in the field of exercise physiology to assess the effects of aerobic training. In training-related studies, increasing $\dot{V}O_{2max}$ of well-trained runners is generally explained by the fact that, during training, exercises allow a high percentage of $\dot{V}O_{2max}$ (90–100% $\dot{V}O_{2max}$) to be maintained (Fox 1975; Wenger and Bell 1986; Robinson et al. 1991; Tabata et al. 1996; Jones and Carter 2000). Therefore, it can be assumed that the percentage of $\dot{V}O_{2max}$ attained and the time for which it is sustained above 90% ($t90\dot{V}O_{2max}$) or 95% of $\dot{V}O_{2max}$ ($t95\dot{V}O_{2max}$) could serve as a good criterion to judge the effectiveness of the stimulus. Two exercise models could be used to elicit a high percentage of $\dot{V}O_{2max}$:or even to reach $\dot{V}O_{2max}$: continuous exercises (Hill and Rowell 1997; Hill et al. 1997) as well as intermittent exercises (IE) (Billat et al. 2000; Dupont et al. 2003a, b; Millet et al. 2003a, b; Tardieu-Berger et al. 2004; Midgley and Naughton 2006). Intermittent exercises have been reported to allow increased total exercise duration (t_{lim}) at high intensity (Åstrand et al. (1960) compared with continuous exercises. In a literature review, Midgley and McNaughton (2006) suggested that for high IE (90–105% of $\dot{V}O_{2max}$) to optimize the time spent at or near $\dot{V}O_{2max}$, and allow an optimal enhancement of $\dot{V}O_{2max}$, the exercise and recovery duration should be between 15 and 30 s. The 30 s/30 s (30sIE), consisting in 30 s high intensity exercise alternated with 30 s active recovery, is commonly practiced by athletes. Åstrand et al. (1960) and Gorostiaga et al. (1991) have shown that a 30sIE realized at 100% of $\dot{V}O_{2max}$ with a passive recovery, does not allow subjects to elicit $\dot{V}O_{2max}$. Earlier studies (Millet et al. 2003b; Tardieu-Berger et al. 2004) have investigated the 30sIE realized at supra maximal intensity (105 or 110% of $\dot{V}O_{2max}$) with active recovery (50% of $\dot{V}O_{2max}$). These studies showed that adequate combination between exercise and recovery intensities during 30sIE exercises may allow $\dot{V}O_{2max}$ to be reached but also sustained it [$t90\dot{V}O_{2max} = 338$ s (Millet et al. 2003b); $t95\dot{V}O_{2max} = 178$ s (Tardieu-Berger et al. 2004)]. In these latter studies, the authors focused on the effects of the intensity exercise on $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$. However, during an IE, recovery intensity also has an effect on $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$. Dupont et al. (2003a, b) during a 15sIE intermittent exercise [15 s at 120% of maximal aerobic velocity (MAV) alternated with 15 s recovery] showed that a passive recovery makes it possible to reach $\dot{V}O_{2max}$ and to increase t_{lim}. Currently, the question of an optimal recovery intensity during 30sIE is still an unsolved question. During another high-intensity IE model (around 2 min at 110% of maximal power output until exhaustion, alternated with 5 min active at 20% of $\dot{V}O_{2max}$ or passive recovery repeated four times), Dorado et al. (2004) showed that active recovery enhanced work capacity by increasing the aerobic energy yield compared with passive recovery. Nevertheless, in the latter study, $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ were not calculated. Hence, it is difficult to conclude about the effect of recovery mode on $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ since the protocol in these studies (Dupont et al. 2003a, b; Millet et al. 2003a; Tardieu-Berger et al. 2004) was roughly different. According to Dorado et al. (2004) the increase in aerobic energy yield during IE with active recovery can be explained by the faster $\dot{V}O_2$ kinetics during the high intensity bout preceded by active recovery. This result is in agreement with other studies reporting faster $\dot{V}O_2$ kinetics at the onset of constant intensity exercise when preceded by warm-up (Bangsbo et al. 1994; Geor et al. 2000). The main purpose of this study was therefore to analyze, during a 30sIE, the effects of the recovery mode (active/passive) on $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$. More specifically, it was hypothesized that during a 30sIE, active recovery would allow an increase in $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ due to a decrease in time to achieve 90 or 95% of $\dot{V}O_{2max}$ with active recovery compared with passive recovery. The secondary aim of this study was to improve the knowledge of IE and allow coaches to better prescribe the most effective intermittent session to elicit an optimal solicitation of the aerobic system.

Methods

Subjects

Eight endurance-trained male adolescents volunteered to participate in this study. The subjects taking part in this study were all from the same athletic club. Within the framework of their training sessions, they regularly practiced the 30sIE with an active recovery at 50% of MAV. Subjects were from 15 to 18 years old. Their mean ± standard deviation (SD) for age, mass, and height were 15.9 ± 1.4 years, 57.7 ± 4.8 kg, and 170.6 ± 4.0 cm, respectively. Prior to participation, they underwent a medical examination and were fully informed of the experimental procedures. Parental consent (for the under-age athletes) and written consent were obtained in accordance with the guidelines of the University of Nantes which had approved the experimental protocol and the procedures involved.

Overview

All subjects performed three field tests until exhaustion on a 400-m outdoor tartan track (calibrated with cones) at the same time of the day, with at least 48 h rest between each test. The subjects were required to have their last light meal 3 h before the tests. All tests were completed within 3 weeks. For each test, the subjects were verbally encouraged to run for as long as possible. Tests were stopped when subjects could not maintain the required speed or when the subjects stopped the exercise, judging themselves exhausted. Before the tests, subjects were familiarized with the exercise procedure and with the gas exchange measuring apparatus. Atmospheric conditions were checked before each test ensuring that all sessions were carried out under similar environmental conditions.

Athletes first performed a maximal graded test to determine $\dot{V}O_{2max}$ and MAV. Then, in a random order, they carried out two intermittent exercises consisting of repeating as long as possible 30 s intensive runs alternating with 30 s passive recovery (IE_P) or active recovery at 50% of MAV (IE_A). All tests were immediately followed by a 12 min passive rest period. After the rest period, the subject did 5 min continuous jogging, and after 2 min stretching, they were asked to run as long as possible at MAV plus 1 km h^{-1} (MAV + 1 test). These tests were performed in order to determine the $\dot{V}O_{2max}$ of the day (Dupont et al. 2003b) and more accurately calculate time spent at $\dot{V}O_{2max}$.

Maximal graded test

Green cones were set at 25 m intervals along the track (inside the first line) while red cones were set 2 m behind the green cones. The running pace was set by an examiner, equipped with a whistle and a chronometer, who made a short sound when the subject had to pass by a cone to be able to maintain a constant speed. A longer sound marked the change in the running stage. At each sound, the subject had to be within 2 m of the red cones. When subjects were behind a red cone three consecutive times, the test ended. This test was preceded by a warm-up period composed of 10 min continuous jogging, 5 min of stretching, and five accelerations out of 50 m. The initial speed was 10 km h^{-1} and was increased by 1 km h^{-1} every 3 min. This method is in accordance with previous publications (e.g. Billat et al. 1994). Velocity at the last completed stage was considered as MAV. If the velocity at exhaustion was only maintained for 1 min 30 (half of the stage duration), then MAV was considered to be equal to the velocity during the previous stage plus 0.5 km h^{-1} (Kuipers et al. 1985).

Intermittent exercises

The two intermittent exercises consisted of repeating as long as possible a 30 s run at 105% of MAV alternated with 30 s passive recovery (IE_P, Fig. 1a) or active recovery (IE_A – 50% of MAV; Fig. 1b). For these exercises, the running pace was given by an examiner making sounds at regular intervals (30 s) up to the end of the exercise. During the 30 s exercise and the 30 s active recovery, subjects had to cover a distance determined according by their own MAV. During the recovery period, a longer sound was made at mid-period (15 s) to inform the athletes of the remaining time for the end of recovery. These two tests were preceded by a standardized warm-up which consisted of 10 min continuous jogging, followed by 5 min stretching exercises, and five short bursts of acceleration on the track.

Respiratory gas exchange and heart rate measurements

During all tests, respiratory gas exchange was measured breath-by-breath using a portable telemetric system [Cosmed K4b^2, Rome, Italy; (McLaughlin et al. 2001)] in order to determine minute ventilation ($\dot{V}_E$), tidal volume (V_T), respiratory frequency (fr), $\dot{V}O_2$, carbon dioxide output ($\dot{V}CO_2$), estimated arterial pressure of CO_2 ($PaCO_2$) (Wasserman 1994). Before each test and before each MAV + 1 test, the O_2 and CO_2 analysis systems were calibrated using ambient air and a gas of known O_2 and CO_2 concentrations (16 and 5%, respectively). The calibration of the K4b^2 turbine flow meter was performed using a 3–1 syringe (Quinton Instruments, Seattle, Washington, USA). Heart rate (HR) was continuously monitored (Polar Electro, Kempele, Finland). The cardio-respiratory values were averaged over a 15 s period during the maximal graded test and MAV + 1 tests, and a 5 s period for intermittent exercises.

$\dot{V}O_{2max}$ and $\dot{V}O_{2max}$ of the day calculations

The $\dot{V}O_{2max}$ corresponded to the highest $\dot{V}O_2$ attained in two successive 15 s periods for the maximal graded test. It was judged that subjects had reached their $\dot{V}O_{2max}$ when three or more of the following criteria were met: (1) a steady state of $\dot{V}O_2$ despite increasing running speed (change in $\dot{V}O_2$ at $\dot{V}O_{2max}$ $\leq 150\,\mathrm{ml\,min}^{-1}$) (Taylor et al. 1955); (2) a final respiratory exchange ratio (R_{max}) higher than 1.1; (3) visible exhaustion; (4) an HR at the end of exercise (HR_{max}) within the 10 bpm of the predicted maximum [210 – (0.65 × age) ; (Spiro 1977)].

The $\dot{V}O_{2peak}$ corresponded to the highest $\dot{V}O_2$ attained in two successive 15 s periods for the MAV + 1 test. It was assumed that the measured $\dot{V}O_{2peak}$ corresponded to the $\dot{V}O_{2max}$ of the day if the duration of the MAV + 1 test was at least 2 min (Dupont et al. 2003b).

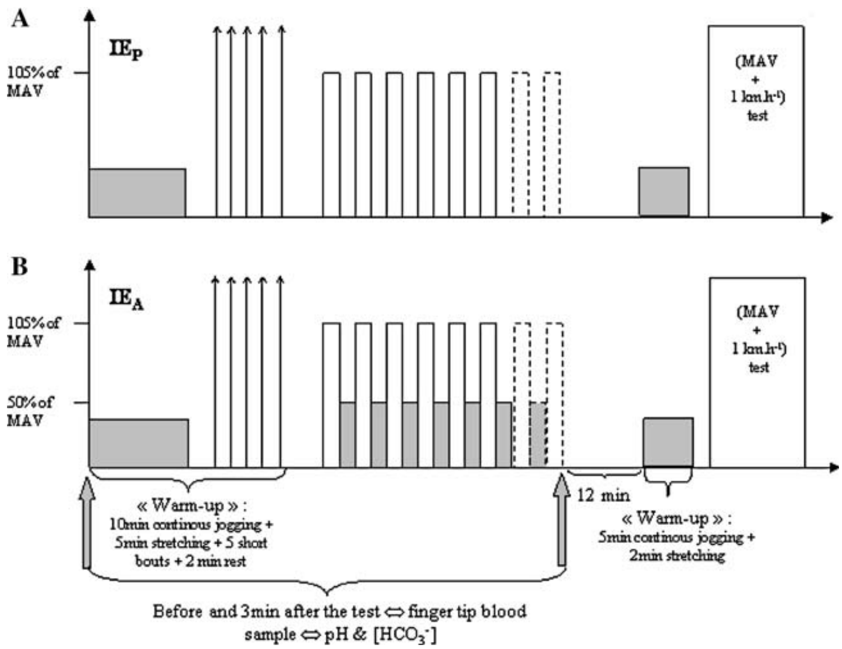

Fig. 1 Experimental protocol for (**a**) IE$_P$ (intermittent exercise maintained until exhaustion with passive recovery) and (**b**) IE$_A$ (intermittent exercise maintained until exhaustion with active recovery – 50% MAV). Both tests were preceded by the same warm-up. MAV: maximal aerobic velocity; [HCO$_3^-$]: bicarbonate ion concentration

Time to exhaustion, time spent above 90 or 95% of $\dot{V}O_{2max}$, baseline $\dot{V}O_2$ values and time to achieve 90 or 95% of $\dot{V}O_{2max}$

Time to exhaustion (t_{lim}) corresponded to the delay between the start and the end of the exercise. Time spent above 90% ($t90\dot{V}O_{2max}$) or above 95% of $\dot{V}O_{2max}$ ($t95\dot{V}O_{2max}$) was determined from the $\dot{V}O_2$ values higher or equal to 90 or 95% of $\dot{V}O_{2max}$ of the day. The $\dot{V}O_2$ values before the exercise were averaged over a 2 min period during IE$_P$ and IE$_A$ to determine the baseline $\dot{V}O_2$ values ($\dot{V}O_{2base}$). Time to achieve 90% (tt90$\dot{V}O_{2max}$) or 95% of $\dot{V}O_{2max}$ ($tt95\dot{V}O_{2max}$) was the time to achieve 90 or 95% of $\dot{V}O_{2max}$ of the day.

Determination of $\dot{V}O_2$ at 50% of MAV

For each subject the $\dot{V}O_2$ at each stage of the graded test was averaged over the last seconds of exercise (30 s). Then, individual $\dot{V}O_2$ vs. velocity relationship were calculated. The $\dot{V}O_2$ values at the last stage were not included in the calculation. The $\dot{V}O_2$ at 50% of MAV were interloped from this relationship.

Determination of the time course of $\dot{V}_E$, V_T, fr, $\dot{V}CO_2$, and estimated $PaCO_2$

$\dot{V}_E$, V_T, fr, and $\dot{V}CO_2$ values were averaged over a 15 s period during IE$_P$ and IE$_A$. Then, the values were averaged over 10 periods, each corresponding to 10% of the durations of individual t_{lim}. The method used to determine the time course of estimated $PaCO_2$ was the same one as that presented above. The time course of $\dot{V}_E$, V_T, fr, $\dot{V}CO_2$, and $PaCO_2$ are presented in Figs. 3 and 4 for a representative subject.

Blood sample collection

Finger tip blood samples (70 µl) were taken at rest and 3 min after exercise for measurement of pH and ion bicarbonate concentration ([HCO$_3^-$]) with an electrolyte portable analyzer (ABL™ 77, SenDx Medical, Inc., USA).

Statistical analysis

The results are expressed as means (±SD). Difference in $\dot{V}O_{2max}$ determined during the maximal graded test and $\dot{V}O_{2max}$ of the day were compared with a one-way repeated-measures analysis of variance (ANOVA). Mean experimental values were compared using paired *t* tests.

Mean metabolic values were compared using two-way ANOVA with repeated measures for the ‘‘time’’ parameter. Honest significant difference (HSD) Tukey and Student–Newman–Keuls post hoc tests were used in the case of significant main effect and interactions, respectively. The size of the effect of recovery intensity was calculated from the Omega square coefficient (ω^2) usually used to asses the amount of variance attributed to each significant effect (Abdi 1987) following the equation:

$$\omega^2 = \left[\left(SS_{Between-subjects} - (k-1) \times \left(MS_{Within-subjects}\right)/\left(SS_{Total} + MS_{Within-subjects}\right)\right] \times 100,\right.$$

where SS is the sum of squares, MS is the mean square, and k is the number of testing times.

For all statistical analyses, a P value of 0.05 (alpha) was accepted as the level of significance. If a difference was not statistically significant at the chosen alpha level, the beta risk of an erroneous conclusion of equivalence was chosen as a P value less than or equal to 0.2.

Results

Maximal graded test and MAV + 1 tests

The mean values for MAV, $\dot{V}O_{2max}$, HR_{max}, and R_{max} were 17.9 ± 0.4 km h^{-1}, 57.4 ± 6.1 ml min^{-1} kg^{-1}, 201.2 ± 8.2 bpm and 1.12 ± 0.05, respectively. The $\dot{V}O_{2max}$ of the day measured during MAV + 1 tests are presented in Table 1. Mean $\dot{V}O_{2max}$ determined during maximal graded test and $\dot{V}O_{2max}$ of the day values obtained during IE_A and IE_P were not significantly different. For each subject a significant relationship was found between $\dot{V}O_2$ and velocity (r^2 = 0.92 ± 0.06). Mean $\dot{V}O_2$ (34.4 ± 4.02 ml min^{-1} kg^{-1}) at 50% of MAV were significantly ($P < 0.05$) higher than mean $\dot{V}O_2$ (28.71 ± 3.07 ml min^{-1} kg^{-1}) at 50% of $\dot{V}O_{2max}$. Mean $\dot{V}O_2$ at 50% of MAV corresponded to 60.2 ± 7.4% of $\dot{V}O_{2max}$.

Intermittent exercises

Mean values for parameters measured during IE are presented in Table 1. t_{lim} was significantly longer ($P < 0.01$) for IE_P than IE_A. In absolute value, there were no significant difference between $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ calculated for IE_P and IE_A ($P > 0.2$). However, in relative value ($\%t_{lim}$) $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ represented a significantly ($P < 0.001$ and $P < 0.05$, respectively) higher percentage of t_{lim} for IE_A than for IE_P. During IE_P one subject failed to reach 95% of $\dot{V}O_{2max}$ of the day, while all subjects reached 95% of $\dot{V}O_{2max}$ of the day for IE_A. For IE_P as for IE_A all subjects reached 90% of $\dot{V}O_{2max}$ of the day. Mean $tt90$ $\dot{V}O_{2max}$ and $tt95$ $\dot{V}O_{2max}$ were not significantly different between IE_P and IE_A.

The pH and $[HCO_3^-]$ mean values revealed significant main recovery intensity effects ($F_{1,14} = 4.66$, $P < 0.05$, $F_{1,14} = 5.91$, $P < 0.05$, respectively), explaining 74% (ω^2) and 23% of the total variance, respectively. The post hoc analysis revealed significant differences ($P <$ 0.05–0.001) between the two conditions of recovery intensity (Fig. 2a, b).

The evolution of $\dot{V}O_2$, fr, V_T, and $\dot{V}_E$ time course and $\dot{V}O_2, \dot{V}CO_2$ and estimated $PaCO_2$ time course during IE_P for one representative subject are presented in Figs. 3 and 4, respectively.

Discussion

The purpose of this study was to compare, during a 30sIE, the effects of the recovery mode (active/passive) on $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$. Short intermittent exercise such as the 30sIE realized at 105% of MAV is of particular interest as it enables subjects to reach and maintain a high percentage of $\dot{V}O_{2max}$ (Millet et al. 2003a). In this study the choice of exercise intensity was based on previous studies. Indeed, supra-maximal (>100% of MAV) 30sIE have been shown to allow the improvement of endurance performance (Septo et al. 1999; Tabata et al. 1996) thanks to an increase in $\dot{V}O_{2max}$ which seems to be due, in particular, to the increase in oxidative enzyme activities (citrate synthase, succinate dehydrogenase) (Holloszy et al. 1984). Many authors have hypothesized that the $\dot{V}O_{2max}$ improvement with training is correlated with time

Table 1 Mean (±SD) data measured for the two intermittent exercises with passive (IE_P) and active (50% of MAV – IE_A) recovery

Test	VO_{2max} of the day (ml min^{-1} kg^{-1})	t_{lim} (s)	$t90VO_{2max}$ (s)	$t90VO_{2max}$ (% t_{lim})	$t95VO_{2max}$ (s)	$t95VO_{2max}$ ($\%t_{lim}$)	VO_{2base} (ml min^{-1} kg^{-1})	$tt90VO_{2max}$ (s)	$tt95VO_{2max}$ (s)
IE_A	57.8^{NS} (8.4)	1072^{**} (388)	746^{NS} (417)	67.7^{***} (19)	459^{NS} (332)	42.1^{*} (27)	10.94^{NS} (2.6)	82^{NS} (43)	121^{NS} (77)
IE_P	55.0 (7.2)	2145 (829)	548 (499)	24.2 (19)	316 (360)	13.8 (15)	12.91 (3.2)	113 (100)	164 (218)

VO_{2max} of the day: VO_{2max} determined during the MAV + 1 test; t_{lim}: total exercise duration; $t90VO_{2max}$: time spent above 90% of VO_{2max} of the day expressed in absolute (s) and in relative ($\%t_{lim}$) values; $t95VO_{2max}$: time spent above 95% of $VO_{2max}$of the day expressed in absolute (s) and in relative ($\%t_{lim}$) values; VO_{2base}: mean values of VO_2 over 2 min before the exercise; $tt90VO_{2max}$: time to achieve 90% of VO_{2max}; $tt95VO_{2max}$: time to achieve 95% of VO_{2max}

NS: no significant difference

Significant difference between IE_A and IE_P; *$P < 0.05$; ** $P < 0.01$; ***$P < 0.001$

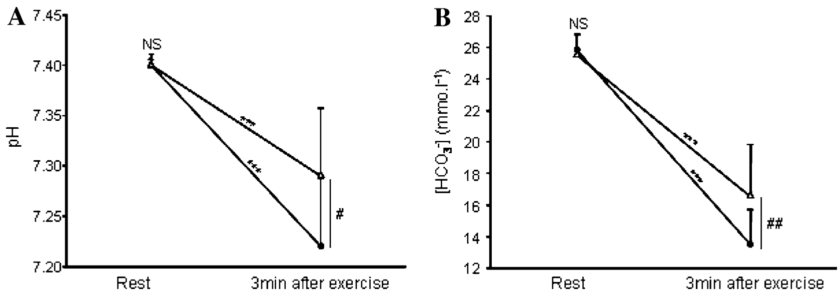

Fig. 2 Mean (±SD) pH (**a**) and bicarbonate ion concentration ($[HCO_3^-]$) (**b**) measured at rest and 3 min after intermittent exercise with passive (IE_P) and active (50% of MAV – IE_A) recovery. ● indicates IE_A. △ indicates IE_P. Significant difference: *** $P < 0.001$; # $P < 0.05$; ## $P < 0.01$

spent at a high level of oxygen uptake (close to $\dot{V}O_{2max}$) during each exercise session (Hermansen 1981; Hill and Rowell 1997; Billat et al. 2000). Thus, for some years, $t95\dot{V}O_{2max}$ (or $t90\dot{V}O_{2max}$) value has generally been measured (Millet et al. 2003a; Dupont and Berthoin 2004; Tardieu-Berger et al. 2004). Millet et al. (Millet et al. 2003b) have shown that during 30sIE (active recovery), $t95\dot{V}O_{2max}$ was longer when subjects ran at 105% of velocity associated with $\dot{V}O_{2max}$ (v $\dot{V}O_{2max}$) compared with 30sIE at 100% of v $\dot{V}O_{2max}$. These results support the choice of exercise intensity (105% of MAV) in the present study. The active recovery intensity at 50% of MAV has been adopted because it is certainly one of the most chosen

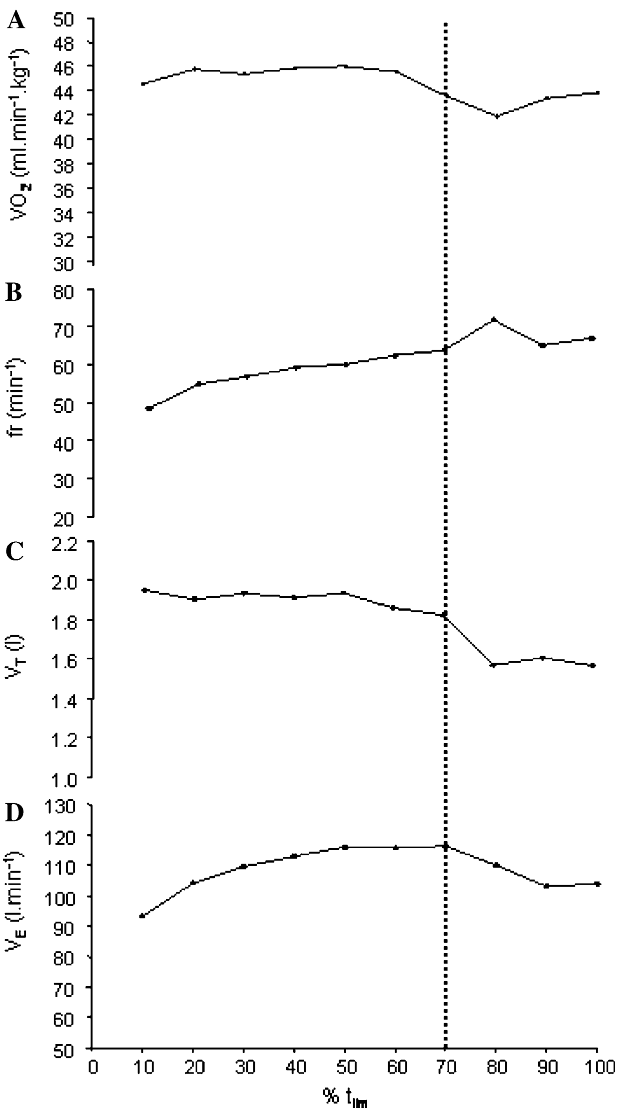

Fig. 3 Time course of oxygen consumption ($\dot{V}O_2$, A), respiratory frequency (fr, B), tidal volume (V_T, C) and ventilation ($\dot{V}_E$, D) during intermittent exercises with passive recovery for one representative subject

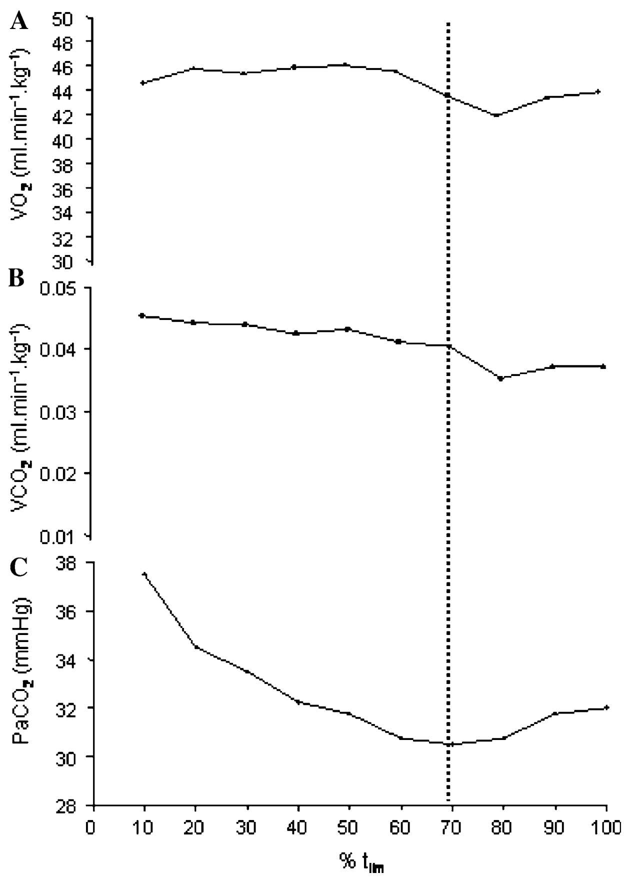

Fig. 4 Time course of oxygen consumption ($\dot{V}O_2$, A), carbon dioxide output ($\dot{V}O_2$, B) and estimated arterial pressure of CO_2 ($PaCO_2$, C) during intermittent exercises with passive recovery for one representative subject

in the scientific literature (Billat et al. 2000; Millet et al.2003a, b; Tardieu-Berger et al. 2004) and because it is a current intensity used by the athletes during their training sessions. This intensity is generally chosen as it allows a higher lactate removal, even if the link between lactate removal and a better recovery could be discussed (Gisolfi et al. 1966; Baldari et al. 2005). Two previous studies realized on the treadmill showed that the best lactate elimination occurs for recovery intensities of 52% (Gisolfi et al. 1966) and 63% of $\dot{V}O_{2max}$ (Hermansen and Stensvold 1972). In the present study, recovery intensity at 50% of the MAV corresponds to an average value of 60.2% of $\dot{V}O_{2max}$.

In the present study, it was hypothesized that during a 30sIE, active recovery would allow an increase in $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ due to a decrease in time to achieve 90 or 95% of $\dot{V}O_{2max}$ with active recovery compared with passive recovery. Our findings are likely to suggest that t_{lim} was significantly longer during IE_P than IE_A. However, $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ were not significantly different ($P >$ 0.2) according to the recovery mode (Table 1). Similarly, $tt90\ \dot{V}O_{2max}$ and $tt95\ \dot{V}O_{2max}$ were not significantly different between IE_P and IE_A ($P > 0.2$). In this line, our hypothesis seems to be not verified. Our results differ from the scientific literature which brings back faster $\dot{V}O_2$ kinetics during an intermittent exercise with an active recovery compared with a passive recovery (Dorado et al. 2004). In the present study, the $\dot{V}O_{2base}$ values before IE_P and IE_A could not explain similar $tt90\ \dot{V}O_{2max}$ or $tt95\ \dot{V}O_{2max}$ values. The lack of difference in $tt90\ \dot{V}O_{2max}$ or $tt95\ \dot{V}O_{2max}$ between IE_P and IE_A could be explained by the fact that recovery intensity chosen for IE_A was not high enough. Indeed, Gerbino et al. (1996) or MacDonald et al. (1997) found that prior moderate exercise had no effect on the subsequent $\dot{V}O_2$ kinetic during heavy exercise while prior heavy exercise significantly speeded the $\dot{V}O_2$ kinetics during subsequent heavy exercise. Another hypothesis is that beneficial effects or otherwise of prior exercise are likely to depend on many factors, including prior exercise and recovery durations (Jones et al. 2003). The 30sIE model of the present study is an alternation of short (30 s) exercise and recovery periods. The influence on $\dot{V}O_2$ kinetics during the subsequent heavy exercise was observed when long prior exercise (> than 2 min) was followed by 2, 6 or 12 min of recovery (Dorado et al. 2004; Gerbino et al. 1996). We can hypothesise that, if the recovery is short (30 s) the $\dot{V}O_2$ prior to the start of each high intensity bout is already high, even during passive recovery and, hence, it is less likely to observe a significant acceleration of the time course of $\dot{V}O_2$, but because the time course is already as fast as it can be. Other studies should, however, be carried out to confirm this hypothesis.

Effects of recovery mode on total exercise duration (t_{lim})

Our results highlight the fact that for a 30sIE at 105% of MAV longer t_{lim} was observed with passive recovery than with active recovery (50% of MAV). Association of the pH decrease and the appearance of fatigue during short intensive exercise have been observed in animals (Metzger and Fitts 1987) and in humans (Hermansen 1981; Sahlin 1983). This relation has been shown in previous studies which have demonstrated that metabolic acidosis, (induced by ammonium chloride ingestion) was associated with a reduction in performance during an intensive exercise on an ergocycle (Jones et al. 1977; Sutton et al. 1981). Recently, Stackhouse et al. (2001) suggested that the muscular contraction process seems to be limited by acidosis which can be considered as the main cause of muscular fatigue during supra-maximal exercise. Taking into account the close relationship which binds the H^+ ions to $[HCO_3^-]$, the concentration decrease in blood $[HCO_3^-]$ seems to account for the acidosis level induced by exercise (Nielsen et al. 2002). Then, the longer t_{lim} observed during IE_P could be explained by the higher pH and $[HCO_3^-]$ values observed at the end of this exercise (Fig. 2a, b). However, fatigue was reached at different pH, meaning that capillary blood pH was not the main factor determining fatigue. In addition, some of these changes may have been elicited by the recovery exercise itself. To rule out the latter we need to know the pH, $[HCO_3^-]$ response to the recovery exercise when performed alone under steady state conditions.

Effects of recovery mode on time spent at high percentage of $\dot{V}O_{2max}$

The two intermittent exercise models led all subjects to reach at least 90% of $\dot{V}O_{2max}$ of the day, but during IE_P one subject failed to reach 95% of $\dot{V}O_{2max}$. These results indicate that, for both IE, the interaction between intensity and duration of exercise and recovery periods was adequate to allow subjects to reach and to maintain a high percentage of $\dot{V}O_{2max}$. When the recovery periods are sufficiently long (at least 30 s), active recovery is generally recommended to increase performance (Signorile et al. 1993; Bogdanis et al. 1996). As indicated by the P values ($P >$ 0.2), our findings might suggest that recovery mode has no influence on $t95\dot{V}O_{2max}$ (or $t90\dot{V}O_{2max}$) in absolute values. Our results show that during the 30sIE, both recovery mode allow similar amounts of time spent at or near $\dot{V}O_{2max}$ and should therefore impose similar levels of stimuli on the oxygen transport and utilization systems. It should be mentioned however that when $t95\dot{V}O_{2max}$ (or $t90\dot{V}O_{2max}$) were expressed in relative values (%t_{lim}), a significantly higher percentage of t_{lim} for IE_A than for IE_P can be observed. Then, the 30sIE active recovery seems to be more efficient than passive recovery when the sole objective of the exercise is to sustain a high percentage of $\dot{V}O_{2max}$ since one spends proportionally less time running for the same value of $t95\dot{V}O_{2max}$ (or $t90\dot{V}O_{2max}$). Nevertheless, Noakes (1991) has shown that cardio-ventilatory solicitation is not the only way to develop endurance performance. In fact, t_{lim} at high intensity has an effect on muscular adaptations. Our results show that passive recovery allows a longer time at high intensity and should therefore impose a greater stimulus on the neuromuscular system. In this way, it seems that passive recovery during a 30sIE is also of interest to develop endurance performance. However, it seems necessary to confirm these results during a longitudinal study.

The present results were in line with an earlier study (Dupont and Berthoin 2004), which showed that during a 15sIE (15 s at 120% of MAV alternated with 15 s active or passive recovery), passive recovery induced longer t_{lim} with a similar $t90\dot{V}O_{2max}$ or $t95\dot{V}O_{2max}$. A lower level of $\dot{V}O_2$ throughout the end of IE_P (Fig. 4A) can explain the similar $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$ during IE_P associated with a longer t_{lim}. This decreased $\dot{V}O_2$ before exhaustion could be explained by a $\dot{V}_E$ decrease (Fig. 3D). The decrease in $\dot{V}_E$ begins at around 70% of t_{lim} (Fig. 3D) and could be explained by a decreased V_T (Fig. 3C). Indeed, after 70% of t_{lim}, the increase in fr (Fig. 3B) seems to be insufficient to prevent the decreased V_T. The increased fr, associated with V_T reduction, can be an indirect sign of respiratory muscle fatigue (Gallagher et al. 1985) and can partly explain the decreased $\dot{V}O_2$.

According to the following equation:

$$\dot{V}_E = 863 \times \dot{V}CO_2/[Paco_2 \times (1 - V_D/V_T)]$$
$$(V_D : \text{dead space volume; Whipp etal. 1984})$$

$\dot{V}_E$ and $\dot{V}CO_2$ are coupled one with the other via $PaCO_2$. Indeed, a reduction in $PaCO_2$ requires a greater ventilatory response per unit of CO_2, while an increase in $PaCO_2$ requires less ventilation (Whipp et al. 1984). Hence, in this study our results about hypoventilation before exhaustion were in agreement with the scientific literature. Indeed the decreased $\dot{V}_E$ was associated with an increase in estimated $PaCO_2$ and a decrease in $\dot{V}CO_2$ (Fig. 4).

The decreased $\dot{V}O_2$ before exhaustion has already been observed during continuous t_{lim} realized at 95% of MAV by Perrey et al. (2002). According to these authors, several physiological mechanisms could explain this decreased $\dot{V}O_2$ notably respiratory muscle fatigue (Gallagher et al. 1985) and alteration of arterio-venous O_2 difference. The latter could be due to a vasoconstriction in active lower limb muscles, a decrease in arterial hemoglobin saturation or an inhibition of oxidative phosphorylation (Perrey et al. 2002). However, this possibility has recently been questioned by Gonzales-Alonso and Calbet (2003). These authors showed that leg arterio-venous O_2 difference and O_2 extraction increased progressively until the end of exercise and preclude any sudden drop in O_2 diffusion at the time O_2 delivery to the leg was falling. Thus, the greater decline in convective O_2 transport to the leg muscles is likely to result from a reduction in leg $\dot{V}O_2$ before exhaustion (Gonzalez-Alonso and Calbet 2003). Hence, the reduction in $\dot{V}O_2$ before exhaustion has been hypothesized by Gonzales-Alonso and Calbet (2003) to be due to a decrease in cardiac output (Q) and leg blood flow. The high demand for respiratory muscle blood flow compromises lower limb muscle flow because of sympathetically mediated vasoconstriction (Harms et al. 1997). Moreover, Gonzales-Alonso and Calbet (2003) showed that the impaired systemic and skeletal muscle aerobic capacity that precedes fatigue was largely related to the failure of the heart to maintain cardiac output and oxygen delivery to locomotive muscles. Other studies should however be, carried out to confirm this hypothesis.

Conclusion

In conclusion, although the scientific literature and empirical knowledge advocate active recovery, passive recovery also seems to be adapted to solicit the aerobic system at a high level. Our results are likely to suggest that active recovery allows a shorter t_{lim} with proportionally longer $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$, whereas passive recovery allows a longer running time for similar $t90\dot{V}O_{2max}$ and $t95\dot{V}O_{2max}$. It seems that the two recovery modes are efficient to solicit the aerobic system during an intermittent exercise. These results suggest that the choice of recovery mode depends on exercise objectives. In other words, if the sole objective of a training session is to improve $\dot{V}O_{2max}$, active recovery (at 50% of MAV) should be chosen. A passive recovery should be chosen to both improve

$\dot{V}O_{2max}$ and induce muscular adaptations. Longitudinal studies should be carried out to confirm the interest of passive recovery during short intermittent training to increase aerobic fitness. Moreover, currently, most studies suggest that the percentage of $\dot{V}O_{2max}$ attained and the time for which it is sustained above 90% $\dot{V}O_{2max}$ could serve as good criteria to judge the effectiveness of the stimulus to improve aerobic fitness. It would however be interesting to confirm the relevance of this parameter in the increase of $\dot{V}O_{2max}$ with training studies.

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