THE EFFECTS OF RECOVERY DURATION DURING HIGH-INTENSITY INTERVAL EXERCISE ON TIME SPENT AT HIGH RATES OF OXYGEN CONSUMPTION, OXYGEN KINETICS, AND BLOOD LACTATE

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ABSTRACT

Smilios, I, Myrkos, A, Zafeiridis, A, Toubekis, A, Spassis, A, and Tokmakidis, SP. The effects of recovery duration during high-intensity interval exercise on time spent at high rates of oxygen consumption, oxygen kinetics, and blood lactate. *J Strength Cond Res* 32(8): 2183–2189, 2018—The recovery duration and the work-to-recovery ratio are important aspects to consider when designing a high-intensity aerobic interval exercise (HIIE). This study examined the effects of recovery duration on total exercise time performed above 80, 90, and 95% of maximum oxygen consumption ($\dot{V}O_2$max) and heart rate (HRmax) during a single-bout HIIE. We also evaluated the effects on $\dot{V}O_2$ and HR kinetics, blood lactate concentration, and rating of perceived exertion (RPE). Eleven moderately trained men (22.1 ± 1 year) executed, on 3 separate sessions, 4 × 4-minute runs at 90% of maximal aerobic velocity (MAV) with 2, 3, and 4 minutes of active recovery. Recovery duration did not affect the percentage of $\dot{V}O_2$max attained and the total exercise time above 80, 90, and 95% of $\dot{V}O_2$max. Exercise time above 80 and 90% of HRmax was longer with 2 and 3 minutes ($p \leq 0.05$) as compared with the 4-minute recovery. Oxygen uptake and HR amplitude were lower, mean response time slower ($p \leq 0.05$), and blood lactate and RPE higher with 2 minutes compared with 4-minute recovery ($p \leq 0.05$). In conclusion, aerobic metabolism attains its upper functional limits with either 2, or 3 or 4 minutes of recovery during the 4 × 4-minute HIIE; thus, all rest durations could be used for the enhancement of aerobic capacity in sports, fitness, and clinical settings. The short (2 minutes) compared with longer (4 minutes) recovery, however, evokes greater cardiovascular and metabolic stress and activates to a greater extent anaerobic glycolysis and hence, could be used by athletes to induce greater overall physiological challenge.

KEY WORD heart rate, intermittent, aerobic, training, endurance, metabolism

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INTRODUCTION

High-intensity interval training is an effective method to improve aerobic capacity in athletic and diseased populations (6,9,14,17). The efficacy of interval training for enhancing a wide spectrum of aerobic power measures stems possibly from the cumulative metabolic stress imposed by each training session on the oxygen delivery (central) and oxygen utilization (peripheral) systems. It is proposed that the total exercise time performed above a high percentage of maximal oxygen consumption and heart rate (HR) (i.e., >90% $\dot{V}O_2$max and maximum HR [HRmax]) during an aerobic interval training session reflects the extent of aerobic stress. Thus, exercising at high rates of $\dot{V}O_2$ (above 90% $\dot{V}O_2$max) imposes a greater stress on central and peripheral components of oxygen consumption and might be the most important stimulus for the improvement of aerobic capacity (7,18).

The aerobic metabolic stress of interval exercise depends on the intensity, the duration, and the number of exercise bouts, as well as on the mode, the intensity, and the duration of recovery intervals (2). Most studies manipulated the exercise intensity to examine which interval regime accumulates more exercise time at high rates of $\dot{V}O_2$ (above 90% $\dot{V}O_2$max). It seems that interval protocols attain more exercise time with oxygen consumption above 90% of $\dot{V}O_2$max with exercise intensity of 90–95% of peak aerobic workload/velocity compared with higher intensities (5,24,25) and with interval duration of at least 1 minute compared with those of 30 seconds or less (8,10,12,24). That is, findings are observed irrespective of type of recovery (passive or active) (1,15,16,22,23).

The duration of recovery between exercise bouts is another variable that may affect the exercise time performed at high rates of $\dot{V}O_2$ (above 90% $\dot{V}O_2$max). Increased recovery during an aerobic interval session may result to lower $\dot{V}O_2$ and HR before the start of the subsequent repetition, which in turn may attenuate the peak values achieved during the exercise phase and decrease the total exercise time performed at high rates of $\dot{V}O_2$ and HR. However, oxygen uptake kinetics are faster when exercise starts from a lower metabolic rate (4,20), as is the case with longer rest intervals. Apart from that, modifying the recovery duration and the work-to-recovery ratio during a high-intensity interval exercise, may change the hemodynamic and metabolic challenges placed on the body and alter the contribution of the energy systems to energy production. The only study that manipulated the recovery duration during a high-intensity interval exercise reported that increasing recovery from 1 to 2 minutes between 4-minute runs increased the self-selected running velocities and the average oxygen consumption with no effects on HR and lactate concentrations (13). Increasing further the recovery time between exercise bouts to 4 minutes had no additional effects (13).

Although the above study communicates important information, it does not provide evidence whether the duration of recovery interval may affect the exercise time performed at high rates of $\dot{V}O_2$ (above 90% $\dot{V}O_2$max), an important stimulus for cardiorespiratory and metabolic adaptations during high-intensity aerobic interval exercise (HIIE) training (19). Furthermore, the running velocities in the previous study (13) were not similar across the protocols with different recovery durations. Thus, it is not clear whether the recovery duration per se or the higher speed attained in protocols with longer recovery affected the cardiorespiratory responses. Finally, the oxygen uptake kinetics during long-interval exercise regimes (repeated exercise bouts of 2–5 minutes) as a function of recovery interval of high-intensity interval protocols has yet to be examined. We selected to study the 4 × 4-minute HIIE protocol because this regimen is widely used in sport and clinical settings for the improvement of aerobic fitness (6,9,14,17).

Based on the above, it would be useful to examine whether the recovery duration of a 4 × 4-minute HIIE protocol affects the extent of aerobic system activation. Such knowledge would provide further insights into the physiological responses and the expected long-term adaptations during this type of interval exercise. The aim was to determine the effects of recovery duration on total oxygen consumption and total exercise time performed with $\dot{V}O_2$ and HR above 80, 90, and 95% of $\dot{V}O_2$max and HRmax. We also evaluated oxygen uptake and HR kinetics, blood lactate concentration and the rating of perceived exertion (RPE) during a high-intensity long-interval exercise protocols used to enhance aerobic endurance in athletes, untrained and diseased individuals.

Methods

Experimental Approach to the Problem

All participants completed one maximal incremental test and 3 experimental sessions on a motorized treadmill. Each experimental session started with a warm-up procedure involving running on the treadmill for 7.5 minutes at 60% of maximal aerobic velocity (MAV) and 0.5 minute at MAV, and stretching of the muscles of the lower limbs. Next, the participants completed on 3 separate days 4 runs of 4 minutes at 90% of MAV with either 4 minutes (4:4 protocol), 3 minutes (4:3 protocol), or 2 minutes (4:2 protocol) of active recovery at 35% of MAV. The 3 sessions were performed 5–8 days apart, at room temperature of 21–23° C and relative humidity of 40–50%, in a random order and in a counterbalanced design. Oxygen consumption and HR were continuously measured during all sessions. Blood lactate concentrations were measured before and 3 minutes after the end of the protocols, and the RPE after each repetition. The participants were instructed to avoid any form of exercise 48 hours before each session.

Subjects

Eleven men (mean ± *SD* age: 22.1 ± 1 years, height: 178 ± 8 cm, body mass: 76.3 ± 8.4 kg, $\dot{V}O_2$max: 52.0 ± 4.0 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$, HRmax: 196.6 ± 6.3 $b\cdot min^{-1}$, and MAV: 16.0 ± 1.5 $km\cdot h^{-1}$) volunteered to participate in the study after signing an informed consent form approved by the institutional review board. Participants were recreational runners and were training for aerobic endurance 2–4 times per week for the last 1–3 years, using only the continuous training method. The study was approved by the institutional review board at Democritus University of Thrace.

Procedures

Maximal Incremental Test. All participants performed a maximal incremental test on a treadmill (h/p/cosmos pulsar 3p, Nussdorf-Traunstin, Germany) for the assessment of $\dot{V}O_2$max and MAV. The maximal incremental protocol started at 9 $km\cdot h^{-1}$ and was increased by 1 $km\cdot h^{-1}$ every 2 minutes until volitional exhaustion. Treadmill grade was set at 1% throughout the protocol. Oxygen consumption and HR were continuously measured during testing. Data were calculated in 30-second intervals and the highest values recorded were considered as maximal. The test was considered as maximal when at least 3 of the following criteria were achieved: (a) visual exhaustion of the participants, (b) a plateau in oxygen consumption (<2 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$) despite an increase in running velocity, (c) maximal HR higher than 90% of the predicted maximum (220- age), and (d) maximum respiratory exchange ratio >1.1. As MAV was calculated using the following formula:

$$\text{MAV}\left(\text{km}\cdot\text{h}^{-1}\right) = \text{Velocity of the last completed stage} + (\text{seconds run at the last stage}/120) \quad (1)$$

Exercise Sessions. After arriving at the laboratory, participants started a warm-up procedure consisting of treadmill running for 7.5 minutes at 60% of MAV and 0.5 minutes at MAV and one stretching exercise (2 sets of 20 seconds duration) for thigh, hamstrings, and calf muscles. Then, participants performed 4 runs of 4 minutes at 90% of MAV with either 4 minutes (4:4 protocol), 3 minutes (4:3 protocol), or 2 minutes (4:2 protocol) of active recovery. During recovery, participants were walking at 35% of MAV. One of the researchers was adjusting treadmill speed and was giving feedback to the participants about the remaining time for the completion of the exercise and the recovery phases.

$\dot{V}O_2$ and Heart Rate Data Calculation. Gas exchange was measured breath by breath (K4b²; Cosmed, Rome, Italy) and HR telemetrically (Polar RS400; Polar Electro, Espoo, Finland) throughout the 3 experimental sessions. All data were averaged in 5-second intervals and the following variables were calculated for each interval exercise protocol: (a) the exercise time performed with oxygen consumption and HR equal to or higher than 80, 90, and 95% of $\dot{V}O_2$max and HRmax, (b) the percentage of $\dot{V}O_2$max and HRmax attained during the last 30 seconds of each repetition, and (c) the percentage of $\dot{V}O_2$max and HRmax during the last 20 seconds of each recovery period.

$\dot{V}O_2$ and Heart Rate Kinetics Calculation. To calculate $\dot{V}O_2$ kinetics during the interval exercise protocols, the breath-by-breath data were linearly interpolated to 1-second values. Then all data from the onset to the end of each repetition were fitted using a single exponential growth curve and the amplitude of the $\dot{V}O_2$ increase and the mean response time (MRT), which provides information about the overall $\dot{V}O_2$ response, were calculated. The following formula was used:

$$\dot{V}O_2(t) = \dot{V}O_{2\,\mathrm{baseline}} + A\dot{V}O_2 \times \left(1 - e^{-t/\tau}\right) \qquad (2)$$

Where the $\dot{V}O_2(t)$ represents the $\dot{V}O_2$ at a given time; the $\dot{V}O_{2\,\mathrm{baseline}}$ the mean $\dot{V}O_2$ at the last 20 seconds before the start of each repetition; $A\dot{V}O_2$ the amplitude of the $\dot{V}O_2$ response; and τ the time constant or MRT for this model. Similar calculations were performed for the analyses of HR kinetics.

Blood Lactate. For the measurement of blood lactate concentration, 20 μL of whole blood were collected from the fingertip and were immediately added to 400-μL trichloroacetic acid and centrifuged at 2,500*g* for 15 minutes at room temperature. The supernatant was removed and frozen in −80° C until later analyzed for lactate concentrations using an enzymatic method (Sigma Chemical Co., St Louis, MO, USA; procedure No. 826-UV) that measures the conversion of NAD + to NADH in the presence of lactate dehydrogenase. All samples were analyzed in one batch.

Statistical Analyses

A 1-way repeated-measures analysis of variance (ANOVA) was used to examine the differences among protocols (4:2, 4:3, and 4:4) in (a) exercise time performed with oxygen consumption and HR equal to or higher than 80, 90, and 95% of $\dot{V}O_2$max and HRmax, (b) the percentage of $\dot{V}O_2$max and HRmax during the last 30 seconds of the exercise periods (average of the 4 repetitions) and during the last 20 seconds of the recovery periods (average of the first 3 repetitions), (c) MRT and $\dot{V}O_2$ amplitude (average of the last 3 repetitions), and (iv) RPE values using SPSS statistical software (version 18). A 2-way ANOVA with repeated measures in both factors was used to examine the interaction between exercise protocol (4:2, 4:3, and 4:4) and time point (before and after the exercise protocols) on blood lactate concentrations. Significant differences between mean values were located with the Newman-Keuls test. The level of significance was set at $\alpha = 0.05$. A priori analysis showed that at least 10 subjects were required to detect large differences among mean values with the statistical design performed, with α and power levels set at 0.05 and 0.80, respectively. The effect size (ES) of the differences between mean values was determined using the Cohen's d values (d = [post-test mean − pretest mean]/pooled *SD*). ESs greater than 0.2, 0.5, and 0.8 were interpreted as small, moderate, and large effects, respectively (3).

Results

Oxygen Uptake Parameters

Table 1 presents the $\dot{V}O_2$ uptake parameters in 3 interval exercise protocols with different recovery durations. The percentage of $\dot{V}O_2$max attained ($\dot{V}O_2$peak) during the last 30 seconds of the repetitions was not different among 4:4, 4:3, and 4:2 protocols ($p = 0.57$; $d = 0.16$–0.33; Table 1). One-way ANOVA indicated no significant differences among the 3 exercise protocols for exercise time performed with oxygen consumption above 80% ($p = 0.93$), 90% ($p = 0.31$), and 95% ($p = 0.84$) of $\dot{V}O_2$max (Table 1). The ESs (Cohen's d) for pairwise comparisons between protocols were trivial for exercise time spent above 80% and 95% of $\dot{V}O_2$max ($d = 0.05$–0.19) and trivial to small for the exercise time spent above 90% of $\dot{V}O_2$max ($d = 0.16$–0.49).

As expected, the $\dot{V}O_2$ value at the end of recovery (last 20 seconds) was significantly lower in 4:4 vs. 4:3 and 4:2 protocols and in 4:3 vs. 4:2 protocol ($p = 0.001$–0.01; $d = 0.81$–2.14; Table 1). The $\dot{V}O_2$ kinetics analysis showed a significantly smaller $\dot{V}O_2$ amplitude in 4:2 vs. the 4:4 protocol ($p = 0.01$; $d = 0.96$) with a trend for significant differences between 4:2 vs. 4:3 and 4:3 vs. 4:4 protocols ($p = 0.07$ and 0.09; d: 4:2 vs. 4:3 = 0.57; 4:3 vs. 4:4 = 0.41; Table 1). However, the MRT was slower in the protocol with the smallest recovery duration (4:2) vs. the protocols with greater recovery durations (4:3 and 4:4) ($p = 0.03$; $d = 0.65$ and 0.93); there were no difference in MRT between 4:3 and 4:4 protocols ($p = 0.69$; $d = 0.13$; Table 1).

Table 1. Oxygen uptake ($\bar{x} \pm SD$) parameters with the execution of 4 repetitions of 4-minute duration at 90% of maximal aerobic velocity with 2 (4:2), 3 (4:3), and 4 (4:4) minutes of recovery duration between repetitions.

	4:2	4:3	4:4
Oxygen uptake ($\dot{V}O_2$) parameters			
Average $\dot{V}O_2$, last 30 s of repetitions (%$\dot{V}O_2$max)	96.79 ± 5.29	95.79 ± 3.27	95.14 ± 4.72
Exercise time >80% $\dot{V}O_2$max (s)	775.43 ± 44.30	751.36 ± 57.54	748.73 ± 58.66
Exercise time >90% $\dot{V}O_2$max (s)	546.36 ± 135.37	520.91 ± 174.44	462.73 ± 198.02
Exercise time >95% $\dot{V}O_2$max (s)	265.00 ± 228.92	275.91 ± 208.78	234.09 ± 231.04
$\dot{V}O_2$, last 20 s of recovery (%$\dot{V}O_2$max)	48.06 ± 3.47*†	43.49 ± 4.39*	40.12 ± 3.92
Average mean response time (s)	56.72 ± 8.87*†	50.80 ± 9.21	49.77 ± 5.86
Average $\dot{V}O_2$ amplitude ($ml^{-1}\cdot kg^{-1}\cdot min^{-1}$)	26.53 ± 2.06*	28.02 ± 3.09	29.42 ± 3.74

*$p \leq 0.05$ from 4:4.
†$p \leq 0.05$ from 4:3.

Heart Rate Parameters

Table 2 presents the HR parameters in 4:2, 4:3, and 4:4 interval exercise protocols. The percentage of HRmax achieved during the last 30 seconds of the repetitions was similar across the 3 interval protocols ($p = 0.25$; d: 4:2 vs. 4:3 = 0.03; 4:2 vs. 4:4 = 0.47, 4:3 vs. 4:4 = 0.43; Table 2). Pairwise comparisons revealed significant differences of moderate ES between 4:2 and 4:3 vs. the 4:4 protocol for the exercise time completed above 80% of HRmax ($p = 0.05$; $d = 0.62$ and 0.68) and above 90% of HRmax ($p = 0.04$ and 0.07; $d = 0.67$ and 0.61); there were no difference between the 4:2 and the 4:3 protocols ($p = 0.67$ and 0.9; $d = 0.04$ and 0.10 for 80 and 90% HRmax, respectively). For exercise time performed at HRs above 95% of HRmax, the differences among protocols were not significant and of trivial to moderate ES ($p = 0.22$; d: 4:2 vs. 4:3 = 0.16, 4:2 vs. 4:4 = 0.55, 4:3 vs. 4:4 = 0.40; Table 2).

The HR at the end of recovery (last 20 seconds) gradually decreased with increasing recovery duration of protocols ($p = 0.001$–0.01; $d = 0.64$–1.45; Table 2). Similarly, the amplitude of HR increase was significantly lower in 4:2 vs. the respective values in 4:3 and 4:4 protocols and lower in 4:3 vs. 4:4 protocol ($p = 0.001$–0.01; $d = 0.71$–1.57; Table 2). The MRT for HR was slower in 4:2 protocol compared with the respective values in 4:3 and 4:4 protocols ($p = 0.001$; $d = 1.27$ and 1.43); no difference was observed between 4:3 and 4:4 protocols for MRT ($p = 0.54$; $d = 0.26$; Table 2).

Blood Lactate and Rating of Perceived Exertion

As illustrated in Figure 1, blood lactate concentrations were similar among protocols before the exercise protocols ($p = 0.72$–0.82; $d = 0.16$–0.43). At the end of the exercise protocols, blood lactate concentrations higher after the 4:2 vs. the 4:4 protocol ($p = 0.02$; $d = 0.54$), whereas no differences

Table 2. Heart rate parameters and RPE ($\bar{x} \pm SD$) with the execution of 4 repetitions of 4-minute duration at 90% of maximal aerobic velocity with 2 (4:2), 3 (4:3), and 4 (4:4) of recovery duration between repetitions.*

	4:2	4:3	4:4
HR parameters			
Average HR, last 30 s of repetitions (%HRmax)	93.42 ± 2.93	93.34 ± 3.17	92.05 ± 2.89
Exercise time >80% HRmax (s)	808.18 ± 76.30†	816.36 ± 85.88†	765.91 ± 60.20
Exercise time >90% HRmax (s)	489.09 ± 200.04†	480.91 ± 221.17	345.91 ± 224.56
Exercise time >95% HRmax (s)	162.27 ± 175.11	135.00 ± 155.37	80.55 ± 116.06
HR, last 20 s of recovery (%HRmax)	71.61 ± 6.09†‡	67.10 ± 6.44†	63.33 ± 5.28
Average mean response time (s)	75.63 ± 15.02†‡	57.51 ± 9.82	59.95 ± 8.79
Average HR amplitude ($b\cdot min^{-1}$)	48.54 ± 9.03†‡	55.17 ± 8.66†	60.31 ± 5.51
RPE			
RPE at the end of protocols	15.30 ± 2.11†	15.10 ± 2.42†	14.10 ± 2.08

*HR = heart rate; RPE = rating of perceived exertion.
†$p \leq 0.05$ from 4:4.
‡$p \leq 0.05$ from 4:3.

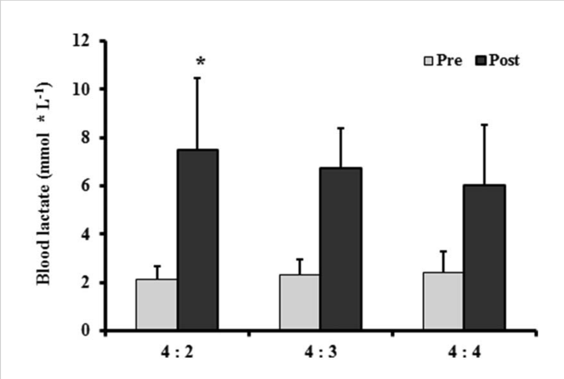

Figure 1. Blood lactate concentrations ($\bar{x} \pm SD$) with the execution of 4 repetitions of 4-minute duration at 90% of maximal aerobic velocity with 2 (4:2), 3 (4:3), and 4 (4:4) of recovery duration between repetitions. $^*p \leq 0.05$ from 4:4.

were detected between the 4:3 vs. the 4:2 protocol ($p = 0.14$; $d = 0.32$) and the 4:3 vs. the 4:4 protocol ($p = 0.17$; $d = 0.34$). Rating of perceived exertion was significantly greater after the 4:2 and 4:3 vs. the 4:4 protocol ($p = 0.05$; $d = 0.57$ and 0.44), whereas no differences were detected between the 4:2 and the 4:3 protocols ($p = 0.67$; $d = 0.09$).

Discussion

The recovery duration and the work-to-recovery ratio are important aspects to consider when designing a HIIE. To the best of our knowledge, this is the first study to compare the extent of the aerobic system activation and oxygen kinetics of a long-interval HIIE protocol using different recovery duration and work-to-recovery ratio. The novel findings of our study are (a) the duration of active recovery (i.e., 2, 3, or 4 minutes) does not affect the total exercise time performed at high rates of oxygen consumption (i.e., above 80, 90, or 95% of $\dot{V}O_2$max) and the percentage of $\dot{V}O_2$max attained at the completion of protocols, suggesting similar overall stress placed on the oxidative system for energy production; as a result, the aerobic metabolism reaches its upper functional limits for energy production with either 2 or 3 or 4 minutes of active recovery at very low intensity (i.e., 35% of MAV) during the 4-minute repetitions at high-intensity of exercise (4 × 4-minute runs at 90% of MAV), (b) the increase in recovery duration modifies the $\dot{V}O_2$ and HR kinetics by increasing the amplitude and reducing the MRT, and (c) the overall physiological/metabolic stress and effort may be higher using the shorter recovery interval, as suggested by greater exercise time performed above >90% of HRmax, RPE scores and blood lactate concentration.

Exercising at a high percentage of $\dot{V}O_2$max (>90% of $\dot{V}O_2$max) may greatly stress the oxygen delivery and utilization systems. The longer the exercise time at this intensity, the most optimal the training stimulus seems to be for the improvement of aerobic capacity (19). It has been suggested that the exercise time above a high percentage of $\dot{V}O_2$max during high-intensity interval exercise is generally determined by the intensity, the duration and the number of exercise bouts and by the mode, the intensity and the duration of the recovery intervals (2). Although this is true for most features of HIIE, this study provides experimental evidence that during long-interval HIIE protocols the recovery duration does not affect the exercise time performed at high rates of oxygen consumption (above 80, 90, and 95% of $\dot{V}O_2$max) as well as the peak $\dot{V}O_2$ values attained during each repetition and at the completion of HIIE. These findings pertain to similar stress of the aerobic energy metabolism regardless of the duration of recovery intervals during HIIE. However, whether HIIE protocols with different recovery durations may elicit similar long-term training adaptations should be examined experimentally, considering the greater overall physiological/metabolic stress and effort exerted during HIIE protocol with shorter recovery interval. It is believed that an aerobic HIIE should allow the accumulation of 5–10 minutes of exercise with oxygen uptake >90% of $\dot{V}O_2$max for optimum adaptations (2). This study shows that the 4:4-, 4:3-, and 4:2-minute HIIE protocols at 90% of MAV allowed the accumulation of 7.7, 8.7, and 9.1 minutes, respectively, of exercise at high oxygen uptake. This may justify the effectiveness of all 3 protocols for improving aerobic capacity.

As expected, $\dot{V}O_2$ levels were restored (decreased) to a greater extent at the end of the recovery as the recovery duration of HIIE protocols increased. Hence, participants were starting the subsequent repetition from lower $\dot{V}O_2$ levels during the 4:4 protocol compared with the 4:2 protocol. Exercise time at a high percentage of $\dot{V}O_2$max, however, was relatively similar among the protocols. The basic analysis of $\dot{V}O_2$ kinetics revealed that the $\dot{V}O_2$ MRTs were faster, and the amplitudes of increase were larger in the 4:4 protocol. This results are in context with previous studies reporting faster oxygen uptake kinetics when exercise starts from a lower metabolic rate (4,20). Thus, the similar exercise times at high percentages of $\dot{V}O_2$max in 4:4 and 4:2 protocols might be the result of the counteractive effects of the reduced metabolic rate before subsequent exercise bout during 4:4 protocol on 2 $\dot{V}O_2$ kinetic parameters that determine the magnitude of $\dot{V}O_2$ response. It seems that the $\dot{V}O_2$ kinetics are adjusted in a manner to regulate the oxygen supply that corresponds to the metabolic requirements of the exercise stimulus.

In agreement with our study, Seiler and Hetlelid (13) did not observe any significant differences in oxygen consumption in the last 3 minutes during each of six 4-minute runs with recovery duration of either 2 or 4 minutes. In the later study, the intensity of exercise bouts was not controlled. That is, the well-trained runners, who had great experience in HIIE, self-selected their running velocity with the aim to complete the protocol with the highest possible velocity. The results of our study extend these previous findings to predetermined and fixed velocities conditions, which are more feasible to use with moderately trained or recreational athletes as well as in populations with chronic diseases that follow rehabilitation programs. In addition, in Seiler and Hetlelid (13) study, when the athlete's self – selected their recovery duration, they chose 118 ± 23 seconds. It should be noted that in our study, although no significant differences in mean values, using conventional statistical approach, were observed between the 4:2 and the 4:4 protocols on exercise time with high rates of oxygen uptake, the exercise time above 90% of $\dot{V}O_2$max ES for the difference between the 2 protocols was moderately higher ($d = 0.49$) with the 4:2 protocol. Therefore, a 2-minute recovery interval during repeated 4-minute runs at 90% of MAV might give an edge to achieve better long-term training adaptations than a 4-minute recovery. This is also supported by the fact that the 4:2 protocol was perceived as more stressful from the participants and activated more anaerobic glycolysis, as evident by higher RPE and blood lactate values, compared with the 4:4 protocol. This view is in accordance with the centrally regulated effort model, suggesting high association between the rise in RPE and changes in peripheral metabolic compounds during exercise at moderate-to-high intensities (11).

Exercise times above a high percentage of HRmax (>80 and 90% of HRmax) were moderately higher with the 2-minute than with 4-minute recovery. This occurred despite the faster HR kinetics observed in the 4:4 protocol. The faster MRT in the protocol with the longer recovery was not enough to compensate the lower HR values at the end of the 4-minute recovery interval compared to the 2-minute. The higher HR at the end of the recovery phase when implementing HIIE protocols with shorter recovery duration indicates a higher cardiovascular stress that sport scientists and clinicians might consider when prescribing interval training in individuals with low training experience or chronic diseases. The measurement of other parameters (i.e., stroke volume, blood pressure, myocardial stress, metabolic pathways) is needed, however, to fully evaluate the load placed on the cardiovascular system and whether the recovery duration modifies the contribution of central and peripheral determinants to oxygen consumption. It should be noted that although no significant differences were observed among protocols on exercise time above high percentages of $\dot{V}O_2$max, the exercise time above high percentages of HR were higher in the 4:2 protocol. Therefore, HR may not precisely represent the aerobic metabolic requirements of an interval session. In any case, end HR values were relatively similar among protocols, and these values may be a better indicator of the overall physiological/metabolic stress of HIIE protocols (21).

The findings of this study are limited to a HIIE session with a fixed number of repetitions and to a 4 × 4 minutes HIIE protocol. It is not clear whether the results would have been different, if the 3 HIIE protocols were performed until exhaustion. Considering, however, the slightly lower lactate and RPE values in 4:4 protocol, a longer recovery interval would allow the execution of an additional repetition(s) and consequently more exercise time with high oxygen uptake. This would most likely provide a better stimulus for aerobic adaptations using the 4:4 HIIE regime. Nevertheless, only few exercise sessions are performed until exhaustion and mostly by athletes. Thus, the study of aerobic system activation with a fixed number of repetitions is valuable for exercise prescription particularly for moderately trained individuals, fitness enthusiasts, and disease populations who are not able to self-select the appropriate exercise intensity to achieve optimum physiological stress.

In conclusion, the 4 × 4-minute HIIE protocol at 90% of MAV activates to a great and similar extent the aerobic system using either 2-, 3-, or 4-minute recovery durations between the exercise bouts. That is, the recovery duration and work-to-recovery ratio do not affect the percentage of $\dot{V}O_2$max attained and the total exercise time performed at high rates of oxygen consumption (i.e., above 80, 90, or 95% of $\dot{V}O_2$max). Increasing the recovery duration during 4 × 4-minute HIIE protocols results to opposite effects on amplitude and on MRT of $\dot{V}O_2$ (increase and reduction, respectively), which may account for the similarity in exercise time at high rates of oxygen consumption in HIIE protocols with different recovery duration. The overall physiological/metabolic stress and effort, however, may be higher using short (2 minutes) recovery intervals, as suggested by greater exercise time performed at high HRs, rate of perceived exertion scores, and blood lactate. Whether HIIE protocols with different recovery duration elicit similar or different long-term training adaptations should be further examined.

Practical Applications

Knowing the effects of a single training characteristic of HIIE protocols on aerobic system activation and on metabolic perturbation may assist exercise scientists and coaches in the selection of the most appropriate form of an aerobic interval session considering the individual characteristics, the training objectives and the training period. The use of a short (2 minutes) compared with longer (4 minutes) recovery interval during the execution of 4 × 4 minutes exercise bouts at 90% of MAV does not substantially affect the exercise time performed at near maximal rate of oxygen consumption, but results to greater cardiovascular stress, as evident by higher HRs, and activates more the anaerobic glycolysis. Therefore, this exercise session elicits greater physiological and metabolic stress and could be used by competitive or recreational athletes when greater system overload is desired. The use of longer interval duration (4 minutes) seems to be less stressful, because less time is spent at high HRs and lower lactate and RPE values are attained with no considerable differences in exercise time at high oxygen consumption rates. So, it could be an appropriate selection when prescribing aerobic exercise to fitness enthusiasts and for rehabilitation to individuals with chronic diseases or even for athletes in training periods with lower physiological stress.

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