$\dot{V}O_2$ Responses to Intermittent Swimming Sets at Velocity Associated With $\dot{V}O_2max$

Sebastien Libicz, Belle Roels, and Gregoire P. Millet

Catalogue Data
Libicz, S.; Roels, B.; and Millet, G.P. (2005). $\dot{V}O_2$responses to intermittent swimming sets at velocity associated with $\dot{V}O_2$max. **Can. J. Appl. Physiol.** 30(5): 543-553. © 2005 Canadian Society for Exercise Physiology.

Key words: *interval training, maximal oxygen consumption, triathletes*
Mots-clés: *entraînement par intervalles, consommation maximale d'oxygène, triathlonien*

Abstract/Résumé

While the physiological adaptations following endurance training are relatively well understood, in swimming there is a dearth of knowledge regarding the metabolic responses to interval training (IT). The hypothesis tested predicted that two different endurance swimming IT sets would induce differences in the total time the subjects swam at a high percentage of maximal oxygen consumption ($\dot{V}O_2max$). Ten trained triathletes underwent an incremental test to exhaustion in swimming so that the swimming velocity associated with $\dot{V}O_2max$ ($v\dot{V}O_2max$) could be determined. This was followed by a maximal 400-m test and two intermittent sets at $v\dot{V}O_2max$: (a) 16 × 50 m with 15-s rest (IT_{50}); (b) 8 × 100 m with 30-s rest (IT_{100}). The times sustained above 95% $\dot{V}O_2max$ (68.50 ± 62.69 vs. 145.01 ± 165.91 sec) and 95% HRmax (146.67 ± 131.99 vs. 169.78 ± 203.45 sec, $p = 0.54$) did not differ between IT_{50} and IT_{100} (values are mean ± SD). In conclusion, swimming IT sets of equal time duration at $v\dot{V}O_2max$ but of differing work-interval durations led to slightly different $\dot{V}O_2$ and HR responses. The time spent above 95% of $\dot{V}O_2max$ was twice as long in IT_{100} as in IT_{50}, and a large variability between mean $\dot{V}O_2$ and HR values was also observed.

Nous connaissons relativement bien les adaptations physiologiques à l'entraînement à l'endurance, mais nous en savons peu sur les adaptations métaboliques dues à l'entraînement par intervalles (IT) à la nage. L'hypothèse suivante a donc été testée: au cours de deux séances d'entraînement par intervalles, le temps total passé à un haut niveau d'effort relatif

The authors are with EA 3759, Faculté des Sciences du Sport, 700 Avenue du Pic Saint Loup, 34090 Montpellier, France.

au $\dot{V}O_2$max diffère d'une séance à l'autre. Dix triathloniens entraînés ont participé à un test d'effort progressif à la nage jusqu'à épuisement et la vélocité correspondant au $\dot{V}O_2$max (v$\dot{V}O_2$max) a été déterminée pendant le test. Ce test fut suivi d'une épreuve sur 400 m et de deux séances d'entraînement par intervalles à v$\dot{V}O_2$max: (a) 16 × 50 m avec des repos de 15 s (IT_{50}); (b) 8 × 100 m avec des repos de 30 s (IT_{100}). Le temps passé à une intensité supérieure à 95% du $\dot{V}O_2$max (moyenne ± écart-type, 68,50 ± 62,69 vs. 145,01 ± 165,91 s) et à 95% HRmax (146,67 ± 131,99 vs. 169,78 ± 203,45 s; p = 0,54) sont semblables d'une séance à l'autre. En conclusion, des séances d'entraînement par intervalles d'égale durée à une intensité correspondant au v$\dot{V}O_2$max, mais avec des ratios effort/repos différents, ne suscitent pas les mêmes ajustements du $\dot{V}O_2$ et de la fréquence cardiaque. Le temps passé à plus de 95% du $\dot{V}O_2$max durant la séance IT_{100} fut deux fois plus important que dans la séance IT_{50}; de plus, nous avons observé des variations importantes des valeurs moyennes du $\dot{V}O_2$ et de la fréquence cardiaque.

Introduction

Interval training (IT) has been proposed as an effective way to improve aerobic capacity in runners (Astrand et al., 1960; Billat et al., 2001), cyclists (Linsday et al., 1996; Stepto et al., 1999), and swimmers (Daniels and Scardina, 1984; Kubukeli et al., 2002). Optimal improvement in cardiorespiratory fitness is thought to occur from training at an intensity corresponding to 90% to 100% of $\dot{V}O_2$max (Billat, 2001a). At the velocity associated with maximal oxygen consumption (v$\dot{V}O_2$max), IT has also been reported to be an efficient means of improving aerobic power and v$\dot{V}O_2$max, both variables being related to performance in endurance sports (Astrand et al., 1960; Billat, 2001a; Gorostiaga et al., 1991; Robinson et al., 1991).

The effects of modifying the work-to-rest ratio, work duration, work intensity, or number of work intervals remains an interesting topic in exercise physiology (Kubukeli et al., 2002), since different combinations of these variables induce different physiological adaptations to the training. Furthermore, it is important to continue investigating different types of IT in order to prescribe more precisely which type of training will maximize the desired adaptations in different individuals. Short duration aerobic IT has been shown to result in less glycogen depletion compared with continuous exercise performed at the same velocity (Billat, 2001a). High intensity exercise undertaken either continuously or intermittently for 60 min was found to result in different muscle glycogen depletion patterns in muscle fibres, thereby indicating different physiological responses (Essen, 1978). It is likely that a short rest of 10 sec was sufficient to regenerate the myoglobin oxygen reserve but not the phosphocreatine reserve. On the other hand, when subjects took longer rest intervals between efforts (30 sec), the velocity reached during the work intervals was 1.5 times greater than that obtained with a rest of only 10 seconds (Billat, 2001a).

The major portion of traditional official swimming events lasts less than 2 minutes. Nonetheless, it has been shown that aerobic power is a paramount factor. For example, Toussaint and Hollander (1994) reported that swimming performance was more improved by a simulated 10% increase in maximal aerobic power than in maximal anaerobic power, namely at the 200- and 400-m events.

In order to measure gas exchange in swimming, a respiratory snorkel

(Toussaint et al., 1987) has been adapted for breath-by-breath gas analysis when connected to a portable metabolic cart. More recently, a modified version of the respiratory snorkel (Aquatrainer®, Cosmed, Rome, Italy) was validated by cycling in laboratory conditions (Keskinen et al., 2003). The respiratory and gas exchange values measured were in accordance with those obtained using the conventional respiratory mask, with only moderate differences of 3–7%.

To date, this device which allows for investigation of gas exchange kinetics during free swimming has been scarcely used (Demarie et al., 2001). Although measurement of gas exchange kinetics is not a new physiological assessment of athletes of other exercise modes (Billat, 2001b; Millet et al., 2003), most swimming studies have been conducted in nonspecific training and competition conditions, such as in a flume or in tethered swimming (Demarie et al., 2001). Technical differences between swimming in a pool vs. in a flume could explain changes in certain physiological parameters such as exercise time to exhaustion at the minimum velocity which elicits $\dot{V}O_2$max and slow-component oxygen uptake. Fernandes et al. (2003b) measured gas-exchange data with the snorkel in free swimming conditions and subsequently confirmed the existence of a slow-component oxygen uptake, as had been observed previously by Demarie et al. (2001). $\dot{V}O_2$ measurements have been conducted in free swimming conditions using direct oxymetry (Bonen et al., 1980), but this method has not yet assessed the physiological responses to swimming IT.

Toubeskis and Tokmakidis (2003) reported that active recovery in swimming may alter the recovery process during repeated sprints. The difficulty of breathing freely is thought to limit oxygen availability and reduce the rate of muscle phosphocreatine resynthesis. It is likely that the mode of exercise (i.e., swimming vs. cycling), type of recovery (active vs. passive), and duration of recovery all influence performance during repeated bouts of high-intensity exercise. In IT involving 50-m efforts, Wakayoshi and Ogita (2003) showed that as the rest period increased, so did the clearance or oxydation of lactate. Despite these results, most studies on swimming IT involved only short distances. The variation in lactate, heart rate, and ammonia responses in swimming IT have been described (Toubeskis and Tokmakidis, 2003; Wakayoshi and Ogita, 2003). Yet the $\dot{V}O_2$ and ventilatory responses have been less well explored in swimming IT.

Consequently, the present study examined two different types of IT sets in swimming in an attempt to gain a better understanding of the cardiorespiratory adaptations to variable durations of work intervals at a high percentage of $\dot{V}O_2$. The hypothesis of this study was that different types of IT in swimming sets would result in differences in the overall time swum at a high percentage of $\dot{V}O_2$, as reported in land human locomotion such as running (Millet et al., 2003).

Methods

Ten trained male triathletes volunteered to participate in the study and provided written informed consent prior to participation. The study was approved by the institutional ethics committee of the Faculty of Sport Sciences (Montpellier, France). All subjects were familiar with the testing procedures. Their physical and training characteristics are listed in Table 1.

Table 1 Physical and Training Characteristics of Participants, *N* = 10 (mean ± *SD*)

Age (years)	22.83	± 4.12
Body mass (kg)	72.25	± 6.61
Height (cm)	180.82	± 7.93
$c\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	68.21**	± 6.83
cHRmax ($bp \cdot m^{-1}$)	188.64*	± 7.53
$s\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	53.01**	± 6.74
sHRmax ($bp \cdot m^{-1}$)	174.78*	± 9.55
400-m speed ($m \cdot s^{-1}$)	1.23	± 0.06
400-m stroke rate ($cycle \cdot min^{-1}$)	37.90	± 3.65
400-m stroke length ($m \cdot cycle^{-1}$)	0.78	± 1.10
Training time ($hr \cdot week^{-1}$)	14.64	± 4.19

Note: Maximum oxygen uptake and heart rate in cycling ($c\dot{V}O_2max$ and cHRmax) and swimming ($s\dot{V}O_2max$ and sHRmax) obtained during cycling and swimming incremental tests to exhaustion. Speed, stroke rate, and stroke length obtained for 400-m swimming test. *$p < 0.05$ for difference between cHRmax and sHRmax; **$p < 0.01$ for difference between $c\dot{V}O_2$ max and $s\dot{V}O_2max$.

EXPERIMENTAL DESIGN

The hypothesis predicted that despite the same total distance swum, a change in the duration of each work-interval performed at $v\dot{V}O_2max$ would induce differences in physiological responses. To test this question, over a period of 3 weeks the subjects performed (a) two maximal incremental tests to exhaustion in cycling and swimming, (b) one 400-m swimming time trial, and (c) two separate swimming IT sets at $v\dot{V}O_2max$: (a) 16 × 50 m with 15-s rest (IT_{50}) and (b) 8 × 100 m with 30-s rest (IT_{100}). All swimming trials involved the front crawl stroke in an indoor 50-m swimming pool with a water temperature of 26 °C.

The average velocity and stroke rate (SR) were measured for each 50 m using a chronometer (Silva, Professional Sports Timer, Paris) with frequency meter. Stroke length (SL) was calculated for each 50 m by dividing the velocity by the SR. For the two IT sessions, the velocity corresponding to $v\dot{V}O_2max$ was controlled by means of a waterproof pacer (Aquapacer, Bristol, U.K.) in the subject's swimming cap. Following the Aquapacer auditory signals, the subject paced himself between colored marks lying every 12.5 m on the bottom of the pool.

The experiment was performed during the winter aerobic basis training. This type of IT is commonly used in swimmers and triathletes during this period, thus the present subjects were used to performing these IT sets. However, they were not allowed to perform these training sessions for 2 weeks prior the experiment.

CYCLING MAXIMAL OXYGEN UPTAKE

Cycling $\dot{V}O_2max$ ($c\dot{V}O_2max$) was determined by a continuous incremental test to exhaustion on an electronically braked cycle ergometer (Ergoline, Bitz, Germany). The workload began at 60 W and was increased by 30 $W \cdot min^{-1}$ until exhaustion. $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$), pulmonary ventilation ($\dot{V}E$), and respiratory exchange ratio (RER) were measured continuously breath by breath using a gas exchange system (K4 b^2, Cosmed). The breath-by-breath data were averaged for each 30-s interval. Heart rate (HR) was continuously monitored using a 12-lead ECG (Marquette Hellige Medical System, Milwaukee, WI). $\dot{V}O_2$ was considered maximal when at least two of the following criteria were met: (a) an increase in $\dot{V}O_2$ of < 100 mL during the last increase in workload, (b) attainment of age-predicted maximal heart rate (210 – [0.65 age] ± 10%), and/or (c) an RER > 1.10.

SWIMMING MAXIMAL OXYGEN UPTAKE

Each subject swam 400 m at maximal intensity so that his swimming performance level could be determined. Velocity and stroke rate were measured for each 50 m of the test (Table 1).

Swimming $\dot{V}O_2max$ ($s\dot{V}O_2max$) was determined by an incremental test to exhaustion. This comprised five 200-m intervals with 15 sec rest after each one; the swimming speed was progressively increased over the test so that each 200 m was completed 5 sec faster. The starting speed was calculated from the subject's time during the 400-m performance test minus 30 sec in order for maximal speed to be reached in the last interval. Speed during the test was controlled via auditory signals that were elicited using the waterproof pacing device coupled with visual marks located on the bottom of the pool every 12.5 m. The incremental swimming tests were validated according to the HR and $\dot{V}O_2$ values recorded by the telemetric K4 b^2 gas exchange system the same way as in the maximal incremental cycling tests.

INTERVAL TRAINING SETS

The athletes performed two IT swimming sets at $v\dot{V}O_2max$. Both sessions comprised a broken 800-m swim, the first involving 16 × 50 m with 15-s rest (IT_{50}) and the second involving 8 × 100 m with 30-s rest (IT_{100}). The swimmer's speed was controlled using the waterproof pacing device previously described. The total amounts of exercising time above 95% $\dot{V}O_2max$ and HRmax were compared between the two IT sets. During the IT sets the respiratory data were stored breath by breath. Data were averaged every 5 sec. Prior to each test the K4 b^2 system was calibrated using ambient air, whose partial O_2 composition was assumed to be 20.9%, and a gas of known O_2 (16%) and CO_2 (5%) concentration. The turbine flow-meter of the K4 b^2 was calibrated with a 3-L syringe (Quinton Instruments, Seattle).

Rate of Perceived Exertion. The subjects indicated their rating of perceived exertion (RPE) after each 200 m during the incremental swim test, each 50 m during IT_{50}, and each 100 m during IT_{100}, by pointing to a level on the 6–20 Borg scale (Borg, 1970).

STATISTICAL ANALYSIS

The results are presented as mean ± *SD*. Normality of the distribution of the variables and the homogeneity of variance were tested and accepted (SigmaStat, Jandel Scientific, San Rafael, CA). A repeated-measures ANOVA and a Tukey post hoc test were employed to identify differences in all parameters between the different trials, and correlations were analysed by the Pearson correlation coefficient. For all statistical analyses, the level of statistical significance was set at $p < 0.05$.

Results

The $\dot{V}O_2$max ($p < 0.01$) and HRmax ($p < 0.05$) differed when measured in the cycling trials compared to the swimming trials (Table 1). RPE values at the end of the swimming and cycling incremental tests were not different: 17.45 ± 1.21 and 17.31 ± 0.95 for cycling and swimming, respectively. Peak $\dot{V}O_2$ values were similar for all three swimming trials: 53.01 ± 6.40; 51.03 ± 3.69; and 52.42 ± 4.35 $ml \cdot kg^{-1} \cdot min^{-1}$ for the incremental test, IT_{50}, and IT_{100}, respectively (Table 2).

The time sustained above 95% $\dot{V}O_2$max did not differ significantly ($p = 0.15$) between IT_{50} and IT_{100}, nor did the time sustained above 95% HRmax ($p = 0.54$) in IT_{50} and IT_{100} (Figure 1). The time the swimmers swam above 95% $\dot{V}O_2$max expressed as a percentage of the total time swum during IT_{50} and IT_{100} (10.61 ± 9.85 vs. 22.01 ± 26.47%) was not statistically different ($p = 0.16$). Similarly, the time spent above 95% HRmax, expressed as a percentage of the total time swum during IT_{50} and IT_{100} (20.46 ± 21.74 vs. 22.67 ± 30.32%), was not different ($p = 0.63$). In all swimming trials, no correlation was found between spatiotemporal parameters (stroke rate and stroke length) and physiological parameters.

Table 2 Swimming Physiological and Technical Parameters (mean ± *SD*)

Parameters	Incremental test	16 × 50 m	8 × 100 m
Speed ($m \cdot s^{-1}$)	1.22 ± 0.06	1.25 ± 0.07	1.23 ± 0.07
Time/50 m (s)	41.22 ± 2.11	40.02 ± 2.23	40.62 ± 2.19
Stroke length ($m \cdot cycle^{-1}$)	0.76 ± 0.09	0.75 ± 0.09	0.73 ± 0.09
Stroke rate ($cycle \cdot min^{-1}$)	37.61 ± 3.42	35.65 ± 3.39	35.65 ± 2.84
$s\dot{V}O_2$peak ($ml \cdot kg^{-1} \cdot min^{-1}$)	53.01 ± 6.74	51.03 ± 3.69	52.42 ± 4.35
mean $s\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	—	40.84 ± 4.14	41.87 ± 4.59
Rate of perceived exertion (points)	17.50 ± 1.20	13.60 ± 1.30	13.70 ± 1.30

Note: For each interval training session (16 × 50 m, 15-s rest, and 8 × 100 m, 30-s rest) and for incremental test to exhaustion (5 × 200 m, 15-s rest after each stage). Swimming $\dot{V}O_2$peak: maximal 5-s averaged values as recorded during last stage of swimming incremental test; mean $s\dot{V}O_2$: averaged $\dot{V}O_2$ between beginning and end of the set.

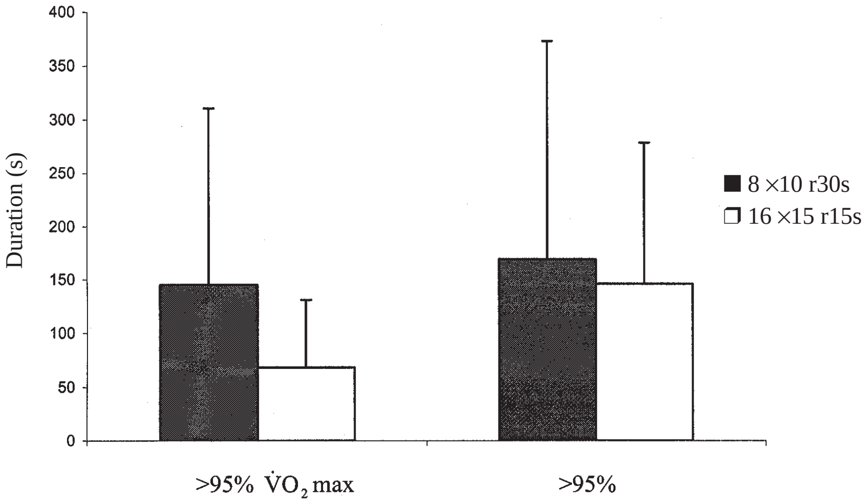

Figure 1. Time spent at >95% maximal heart rate and maximal oxygen uptake for the two interval training sets, 8 × 100 m (r 30 sec) and 16 × 50 m (r 15 sec), swum at $v\dot{V}O_2max$.

Discussion

The principal results of the present study were that intermittent swimming sets of the same overall time swum at $v\dot{V}O_2max$, but with different work-interval durations of 50 m and 100 m (corresponding to 40.02 ± 2.11 vs. 82.56 ± 4.19 s, respectively), led to nonsignificantly different $\dot{V}O_2$ and HR responses in well-trained triathletes. However, the time spent above 95% of $\dot{V}O_2max$ was twice as long in IT_{100} than in IT_{50}, and a large variability between the mean $\dot{V}O_2$ and HR values was also observed. It is noted that $\dot{V}O_2max$ was reached during both IT sets.

In the present study, $s\dot{V}O_2max$ represented only 77% of $c\dot{V}O_2max$. This result is in line with past results from Kreider et al. (1988) of 79%, or from Sleivert and Wenger (1993) of 83%. Furthermore, $s\dot{V}O_2max$ values are in agreement with those previously published (Demarie et al., 2001; Fernandes et al., 2003a) for regional triathletes. In another study, Fernandes et al. (2003b) observed that $\dot{V}O_2max$ in swimming, measured in good swimmers, were higher (76.80 ± 6.50 $ml \cdot kg^{-1} \cdot min^{-1}$) than in the present study (53.01 ± 6.74 $ml \cdot kg^{-1} \cdot min^{-1}$). The fact that our subjects trained intensively in cycling and were not expert swimmers (their velocities corresponding to the maximal 400-m test and to $\dot{V}O_2max$ were 1.23 ± 0.06 $m \cdot s^{-1}$ and 1.22 ± 0.06 $m \cdot s^{-1}$, respectively) may explain the lower values measured in the present study.

In one of the first studies on metabolic responses during intermittent running, Astrand et al. (1960) confirmed that for exercise at 98% $\dot{V}O_2max$, long work periods led to the attainment of $\dot{V}O_2max$ compared to short work periods. Medbo et al. (1988) pointed out that the amount of oxygen stored in the muscular myoglobin is important (≈10% of maximal accumulated oxygen deficit) since it minimizes the cumulative effect of oxygen deficit in short intervals. Accordingly, in the present study the time spent exercising near $\dot{V}O_2max$ was double in IT_{100} compared to IT_{50}. However, due to the large variability in $\dot{V}O_2$ and HR values, the difference was not statistically significant.

Koppo et al. (2002) showed that the time constant of the fast component response was longer during arm exercise than during leg exercise (48 ± 12 vs. 21 ± 5 sec), while the fast component gain was significantly greater during arm exercise (12.1 ± 1.0 vs. 9.2 ± 0.5 $ml \cdot min^{-1} \cdot W^{-1}$. Furthermore, the cardiorespiratory response in swimming may be different compared to other human activities, for the following reasons:

1. Swimming is performed in a horizontal position. Koga et al. (1999) concluded that $\dot{V}O_2$ kinetics is slower in a supine position and during heavy exercise. This may be partly due to an attenuated early rise in heart rate. The supine position also induces an increase of the return of venous blood but reduces blood hydrostatic pressure in the legs (Holmér et al., 1974).

2. Since the body is immersed in water when swimming, pulmonary ventilation must overcome the force of hydrostatic pressure, and subsequently respiratory work could be elevated (Ogita and Tabata, 1992). A lower hyperventilation has been demonstrated during maximal swimming, but gas exchange was sufficient to maintain an oxygenation of arterial blood similar to oxygenation in running (Holmér et al., 1974). Demarie et al. (2001) and Fernandes et al. (2003b) suggested that the major recruitment of fast twitch muscle fibre and the rise of the $\dot{V}O_2$ slow component in swimming is explained by the increasing ventilation output ($\dot{V}E$), which responds to the change in stroke technique (i.e., increased SR) caused by increasing fatigue. In the present study it is of interest to note that the SR was similar in the two IT sets, thereby indicating that this factor alone did not influence the $\dot{V}O_2$ responses.

3. The differences in $\dot{V}O_2$ responses between swimming and running/cycling are consistent with the greater recruitment of type II muscle fibres observed during arm-crank exercise as opposed to those in cycling (Koppo et al., 2002). The mechanical efficiency of swimming is related to the motor recruitment pattern, namely the recruitment of more motor units, particularly low efficiency fast-twitch fibres, and may help explain the differences observed.

4. As for heat conductance of water being higher than for air, body temperature could also influence the cardiorespiratory responses during heavy exercise. Shiojiri et al. (1997) reported the effects of reduced muscle temperature on gas exchange kinetics at the start of exercise. They showed that the amplitude of the primary phase of $\dot{V}O_2$ kinetics decreased, which indicates that cardiac output and stroke volume responses during this phase are reduced under cold conditions.

5. There is evidence of "diving bradycardia" influencing the $\dot{V}O_2$ and HR responses when exercising in water, especially when cold (Stromme et al., 1970).

It is suggested that optimal improvement in aerobic fitness is induced by exercise sustained at an intensity of 90–100% $\dot{V}O_2max$ (Robinson et al., 1991), for a certain length of time (Billat, 2001a). The use of a fixed fraction (50% or >60%) of time to exhaustion (Tlim) has been proposed as a way to individualize training prescription, thus providing greater improvement in aerobic fitness than the classical fixed fraction (Billat, 2001b; Hill and Rowell, 1996, 1997). Hill and Rowell (1996) demonstrated that for a given percentage of Tlim, the time of sustained exercise at or near $\dot{V}O_2max$ differed widely among runners. More recently, Millet et al. (2003) proposed that the use of an individualized fraction of Tlim based on the individualized parameters of $\dot{V}O_2$ kinetics is a more promising alternative. Thus the method for determining the most efficient work-interval duration at $v\dot{V}O_2max$ is still debated and is of considerable interest for physiologists and coaches.

The present study showed that $\dot{V}O_2$ responses are slightly different in swimming IT compared to running IT at $v\dot{V}O_2max$. Further studies are needed in order to determine whether swimming IT with a personalized fraction of work (based on the time to reach 90 or 95% $\dot{V}O_2max$) and rest would result in a more efficient training, that is, with a longer duration of exercise near $\dot{V}O_2max$.

By timing the duration of exercise spent near $\dot{V}O_2max$, the present study suggests that training at or near $\dot{V}O_2max$ would be the optimal intensity to elicit maximum improvements in performance. Unfortunately, this prescription cannot be confirmed without more specific research. In addition, it can be argued that an IT set which allows the longest time at or near $\dot{V}O_2max$ does not necessarily optimize the oxygen transport system to improve endurance performance, especially if, for example, excessive muscular fatigue or acidosis were induced at the same time. However, since the Fick equation describes $\dot{V}O_2max$ as a product of maximal cardiac output ($\dot{Q}max$) and maximal arterial-venous O_2 difference (maximal a–$\bar{v}O_2$ difference), it can be countered that any training-induced increase in the functional capacity of these two factors should enhance $\dot{V}O_2max$, which is predominantly limited by the maximal capacity of the cardiovascular system to transport oxygen to the tissues (Saltin and Rowell, 1980), especially in persons who have a high level of aerobic fitness (Wagner, 2000).

In conclusion, the results of the present study show that swimming sets of the same overall time at $v\dot{V}O_2max$, but with different work-interval durations, leads to slightly different $\dot{V}O_2$ and HR responses in well-trained triathletes. The time spent swimming above 95% $\dot{V}O_2max$ was doubled in the session involving longer intervals (IT_{100}) compared to the session of shorter intervals (IT_{50}), and a large variability in mean $\dot{V}O_2$ and HR values was observed. $\dot{V}O_2max$ was also reached during both the short (~40 s) and long (~80 s) intervals. These findings indicate that the $\dot{V}O_2$ responses during IT in swimming differ from those reported in previous studies on running and cycling. Consequently, methods of individualizing IT as suggested for running or cycling cannot be applied to swimming until further research is carried out. Longitudinal training studies are thus required to clarify and confirm the long-term effects of swimming IT sets.

Acknowledgments

We thank the subjects for their participation and their availability, the staff of the Antigone swimming pool (Montpellier, France), and the Languedoc-Roussillon Triathlon league. We also wish to thank David J. Bentley (Westminster University, U.K.) and Chrissie Bailey (Loughborough University, U.K.) for reviewing the manuscript.

References

Astrand, I., Astrand, P.O., and Christensen, E.H. (1960). Circulatory and respiratory adaptations to severe muscular work. **Acta Physiol. Scand.** 50: 254-258.

Billat, V.L. (2001a). Interval training for performance: A scientific and empirical practice. Part 1: Aerobic interval training. **Sports Med**. 31: 13-31.

Billat, V.L. (2001b). Interval training for performance: A scientific and empirical practice. Special recommendations for middle- and long-distance running. Part II: Anaerobic interval training. **Sports Med.** 31: 75-90.

Billat, V.L., Slawinksi, J., Bocquet, V., Chassaing, P., Demarle, A., and Koralsztein, J.P. (2001). Very short (15s-15s) interval-training around the critical velocity allows middle-aged runners to maintain $\dot{V}O_2$max for 14 minutes. **Int. J. Sports Med.** 22: 201-208.

Bonen, A., Wilson, B.A., Yarkony, M., and Belcastro, A.N. (1980). Maximal oxygen uptake during free, tethered, and flume swimming. **J. Appl. Physiol.** 48: 232-235.

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. **Scand. J. Rehab. Med.** 2-3: 92-98.

Daniels, J., and Scardina, N. (1984). Interval training and performance. **Sports Med.** 1: 327-334.

Demarie, S., Quaresima, V., Ferrari, M., Sardella, F., Billat, V., and Faina, M. (2001). The $\dot{V}O_2$ slow component in swimming. **Eur. J. Appl. Physiol.** 84: 95-99.

Essen, B. (1978). Studies on the regulation of metabolism in human skeletal muscle using intermittent exercise as an experimental model. **Acta Physiol. Scand. Suppl.** 454: 1-32.

Fernandes, R.J., Billat, V.L., Cardoso, C.S., Barbosa, T., Soares, S.M., Ascensão, A., Colaço, P.J., Demarle, A., and Vilas-Boas, J.P. (2003a). Time limit at v$\dot{V}O_2$max and $\dot{V}O_2$max slow component in swimming. A pilot study of university students. In: J.C. Chatard (Ed.), **Proceedings of the IXth World Symposium on Biomechanics and Medicine in Swimming**, pp. 331-336. St Etienne, France.

Fernandes, R.J., Cardoso, C.S., Soares, S.M., Ascensão, A., Colaço, P.J., and Vilas-Boas, J.P. (2003b). Time limit and $\dot{V}O_2$ slow component at intensities corresponding to $\dot{V}O_2$max in swimmers. **Int. J. Sports Med.** 24: 576-581.

Gorostiaga, E.M., Walter, C.B., Foster, C., and Hickson, R.C. (1991). Uniqueness of interval and continuous training at the same maintained exercise intensity. **Eur. J. Appl. Physiol.** 63: 101-107.

Hill, D.W., and Rowell, A.L. (1996). Running velocity at $\dot{V}O_2$max. **Med. Sci. Sports Exerc.** 28: 114-119.

Hill, D.W., and Rowell, A.L. (1997). Responses to exercise at the velocity associated with $\dot{V}O_2$max. **Med. Sci. Sports Exerc.** 29: 113-116.

Holmér, I., Lundin, A., and Eriksson, B.O. (1974). Maximum oxygen uptake during swimming and running by elite swimmers. **J. Appl. Physiol.** 36: 711-714.

Keskinen, K.L., Rodriguez, F.A., and Keskinen, O.P. (2003). Respiratory snorkel and valve system for breath-by-breath gas analysis in swimming. **Scand. J. Med. Sci. Sports** 13: 322-329.

Koga, S., Shiojiri, T., Shibasaki, M., Kondo, N., Fukuba, Y., and Barstow, T.J. (1999). Kinetics of oxygen uptake during supine and upright heavy exercise. **J. Appl. Physiol.** 87: 253-260.

Koppo, K., J. Bouckaert, J., and Jones, A.M. (2002). Oxygen uptake kinetics during high-intensity arm and leg exercise. **Respir. Physiol. Neurobiol.** 133: 241-250.

Kreider, R.B., Boone, T., Thompson, W.R., Burkes, S., and Cortes, C.W. (1988). Cardiovascular and thermal responses of triathlon performance. **Med. Sci. Sports Exerc.** 20: 385-390.

Kubukeli, Z.N., Noakes, T.D., and Dennis, S.C. (2002). Training techniques to improve endurance exercise performances. **Sports Med.** 32: 489-509.

Lindsay, F.H., Hawley, J.A., Myburgh, K.H., Schomer, H.H., Noakes, T.D., and Dennis S.C. (1996). Improved athletic performance in highly-trained cyclists after interval training. **Med. Sci. Sports Exerc.** 13: 190-192.

Medbo, J.I., Mohn, A.C., Tabata, I., Bahr, R., Vaage, O., and Sejersted, O.M. (1988). Anaerobic capacity determined by maximal accumulated O_2 deficit. **J. Appl. Physiol.** 64: 50-60.

Millet, G.P., Candau, R. Fattori, P., Bignet, F., and Varray, A. (2003). $\dot{V}O_2$ responses to different intermittent runs at velocity associated with $\dot{V}O_2max$. **Can. J. Appl. Physiol.** 28: 410-423.

Ogita, F., and Tabata, I. (1992). Oxygen uptake during swimming in a hypobaric hypoxic environment. **Eur. J. Appl. Physiol. Occup. Physiol.** 65: 192-196.

Robinson, D.M., Robinson, S.M., Hume, P.A., and Hopkins, W.G. (1991). Training intensity of elite male distance runners. **Med. Sci. Sports Exerc.** 23: 1078-1082.

Saltin, B., and Rowell L.B. (1980). Functional adaptations to physical activity and inactivity. **Fed. Proc.** 39: 1506-1513.

Shiojiri, T., Shibasaki, M., Aoki, K., Kondo, N., and Koga, S. (1997). Effects of reduced muscle temperature on the oxygen uptake kinetics at the start of exercise. **Acta Physiol. Scand.** 159: 327-333.

Sleivert, G.G., and Wenger, H.A. (1993). Physiological predictors of short-course triathlon performance. **Med. Sci. Sports Exerc.** 25: 871-876.

Stepto, N.K., Hawley, J.A., Dennis, S.C., and Hopkins, W.G. (1999). Effects of different interval-training programs on cycling time-trial performance. **Med. Sci. Sports Exerc.** 31: 736-741.

Stromme, S.B., Kerem, D., and Elsner, R. (1970). Diving bradycardia during rest and exercise and its relation to physical fitness. **J. Appl. Physiol.** 28: 614-621.

Toubeskis, A., and Tokmakidis, S. (2003). Active recovery decreases performance during repeated bouts of sprint swimming irrespective of resting interval duration. In: J.C. Chatard (Ed.), **Proceedings of the IXth World Symposium on Biomechanics and Medicine in Swimming**, pp. 469-474. St Etienne, France.

Toussaint, H.M., and Hollander, A.P. (1994). Energetics of competitive swimming—Implications for training programs. **Sport Med.** 18: 384-405.

Toussaint, H.M., Meulemans, A., de Groot, G., Hollander, A.P., Schreurs, A.W., and Vervoorn, K. (1987). Respiratory valve for oxygen uptake measurements during swimming. **Eur. J. Appl. Physiol. Occup. Physiol.** 56: 363-366.

Wagner, P.D. (2000). New ideas on limitations to $\dot{V}O_2max$. **Exerc. Sport Sci. Rev.** 28: 10-14.

Wakayoshi, K., and Ogita, F. (2003). Determination and validity of internal swim critical velocity in 50 m interval training. In: J.C. Chatard (Ed.), **Proceedings of the IXth World Symposium on Biomechanics and Medicine in Swimming**, pp. 475-480. St Etienne, France.

Received March 5, 2004; accepted in final form December 21, 2004.

Copyright of Canadian Journal of Applied Physiology is the property of Human Kinetics Publishers, Inc.. The copyright in an individual article may be maintained by the author in certain cases. Content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.