\( \dot{V}O_2 \) Responses to Different Intermittent Runs at Velocity Associated With \( \dot{V}O_2 \)max

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Catalogue Data

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Mots-clés: entraînement par intermittence, consommation maximale d’oxygène, performance, temps d’épuisement

Abstract/Resume
The purposes of this study were (1) to determine the time sustained above 90% of \( \dot{V}O_2 \)max in different intermittent running sessions having the same overall time run at the velocity (\( \dot{V}O_2 \)max) associated with \( \dot{V}O_2 \)max, and (2) to test whether the use of a fixed-fraction (50%) of the time to exhaustion at \( \dot{V}O_2 \)max (\( T_{lim} \)) leads to longer time spent at a high percentage of \( \dot{V}O_2 \)max. Subjects were 8 triathletes who, after determination of their track \( \dot{V}O_2 \)max and \( T_{lim} \), performed three intermittent running sessions alternating the velocity between 100% and 50% of \( \dot{V}O_2 \)max, termed 30s~30s, 60s~30s, and \( \frac{1}{2}T_{lim} \)~\( \frac{1}{2}T_{lim} \) where the overall time at \( \dot{V}O_2 \)max was similar (=\( 3 \times T_{lim} \)). \( \dot{V}O_2 \)max achieved in the incremental test was 71.1 ± 3.9 ml·min\(^{-1}\)·kg\(^{-1}\) and \( T_{lim} \) was 236 ± 49 s. \( \dot{V}O_2 \)peak and peak heart rate were lower in 30s~30s than in the other intermittent runs. The time spent above 90% of \( \dot{V}O_2 \)max was significantly (\( p < 0.001 \)) longer either in 60s~30s (531 ± 187 s) or in \( \frac{1}{2}T_{lim} \)~\( \frac{1}{2}T_{lim} \) (487 ± 176 s) than in 30s~30s (149 ± 33 s). \( T_{lim} \) was negatively correlated with the time (in % of \( T_{lim} \)) spent above 90% of \( \dot{V}O_2 \)max in 30s~30s (\( r = -0.75, p < 0.05 \)). \( T_{lim} \) was also correlated with the difference of time spent over 90% of \( \dot{V}O_2 \)max between 60s~30s and 30s~30s (\( r = 0.77, p < 0.05 \)), or between \( \frac{1}{2}T_{lim} \)~\( \frac{1}{2}T_{lim} \) and 30s~30s (\( r = 0.97, p < 0.001 \)). The results confirm that \( \dot{V}O_2 \)max and \( T_{lim} \) are useful for setting interval-training sessions. However,

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the use of an individualized fixed-fraction of \( T_{lim} \) did not lead to longer time spent at a high percentage of \( VO_2\max \) compared to when using a fixed work-interval duration.

The velocity (\( vVO_2\max \)) associated with maximal oxygen consumption (\( VO_2\max \)) has been shown to be closely related to performance in distance running over various distances, for example, distances of 1,500 to 5,000 m (Lacour et al., 1990), 10 km (Morgan et al., 1989), and 21.1 km (Billat et al., 1994). This velocity can be estimated by a variety of methods (Hill and Rowell, 1996) including the ratio between \( VO_2\max \) and the gross energy cost (Di Prampero, 1986) or the net energy cost (Lacour et al., 1990), by using the slope of the relationship between velocity and \( VO_2\max \) (Morgan et al., 1989), or as the lowest velocity at which \( VO_2\max \) is elicited during an incremental exercise test (Billat et al., 1994; Billat and Koralsztein, 1996). It is assumed that if \( vVO_2\max \) is to be used as a guide for the prescribing of training intensities during endurance exercise, then this latest method is more appropriate (Hill and Rowell, 1996) and therefore was chosen in the present study.

Interval training has been proposed as an effective way to improve the aerobic capacity in runners of all levels (Astrand et al., 1960; Billat, 2001; Billat et al., 2000; Tabata et al., 1997). However, the question as to which are the best parameters (e.g., work-interval intensity and duration; recovery-interval type and duration; ratio of work to recovery; number of intervals per set and number of sets; amplitude) during an interval-training session has continued to interest coaches and scientists ever since research was first conducted in this area (Astrand et al., 1960). In the last decade, the individualization—how to define the most appropriate training regimen from one individual to another—of these parameters has
become an important topic in exercise physiology. Yet the question as to which is the most optimal interval-training format remains unanswered.

Recently several studies have evaluated the metabolic changes induced by interval training with the exercise duration ranging between 15 s and $T_{lim}$ for each interval, and exercise intensities between 80% and 120% v$\dot{V}O_2$max (Billat et al., 2000; 2001; Smith et al., 1999). In fact, high-intensity intermittent training has been shown to be an effective means of increasing $VO_2$max (Billat, 2001; Gorostiaga et al., 1991). The question as to which is the most effective work-interval duration for a given individual is still unclear. Franch et al. (1998) investigated the effects of 6 weeks (3 sessions/wk) of either continuous running at 90% v$\dot{V}O_2$max, or of either long-interval (4 min~2 min) or short-interval (15s~15s) training sets at supra-v$\dot{V}O_2$max intensities. $VO_2$max, v$\dot{V}O_2$max, and submaximal running economy increased, respectively, by 5.9%, 9%, and 3.1% for the continuous training; by 6%, 10%, and 3% for long-interval training; and by 3.6%, 4%, and 0.9% for short-interval training. Franch et al. concluded that short-interval training was less efficient for increasing aerobic fitness ($\dot{V}O_2$max, running economy) than were longer work intervals.

The hypothesis that $T_{lim}$ could be used for determining the most adequate work-interval duration at v$\dot{V}O_2$max underlined the proposal that the most adequate duration in intermittent runs at v$\dot{V}O_2$max was $\frac{1}{2}T_{lim}$. Billat et al. (1996) showed that in well-trained runners, with five intervals of $\frac{1}{2}T_{lim}$ duration run at v$\dot{V}O_2$max (with recovery run at 60% of v$\dot{V}O_2$max), the total time spent at VO$_2$max was significantly longer than with a classical 2-min work-interval duration. Moreover, a later study by Billat et al. (1999b) provided further support for this theory in showing the efficiency of $\frac{1}{2}T_{lim}$ as the work-interval duration: after only 4 weeks, v$\dot{V}O_2$max and VO$_2$max increased in trained runners using this kind of interval training. In addition, Smith et al. (1999) found improvements in v$\dot{V}O_2$max, VO$_2$max, and 3,000-m performance in trained runners after only a few weeks when using 60–75% of $T_{lim}$ as the work-interval duration.

The effectiveness of the different combinations of amplitudes, intensities, and work-interval durations remains an open debate. However, it is likely that the key criteria in interval-training efficiency are the percentage of VO$_2$max sustained and the time at which it is maintained during training (Billat, 2001; Demarie et al., 2000; Robinson et al., 1991; Tabata et al., 1997). Therefore, the aim of the present study was to determine the time sustained near or at VO$_2$max in different intermittent running sessions having the same overall run time at the same work-intensity (v$\dot{V}O_2$max). Furthermore, this study tested whether the use of a fixed-fraction (50%) of the time to exhaustion at v$\dot{V}O_2$max ($T_{lim}$) leads to longer time spent at a high percentage of VO$_2$max.

**Methods**

**SUBJECTS**

Eight well-trained triathletes volunteered to participate in this study. Subjects had the following characteristics (mean ± SD): age, 22.6 ± 5.0 yrs; height, 175.1 ± 3.9 cm; weight, 65.9 ± 6.3 kg; training experience, 7.0 ± 2.2 yrs. The study was approved by the institutional ethics committee of Nîmes, France. Each athlete gave written voluntary informed consent prior to participating in the study.
EXPERIMENTAL DESIGN

All subjects underwent five testing sessions on a 400-m synthetic running track over a 3-week period. Each subject performed a maximal incremental test to exhaustion to determine $\dot{V}O_2$ max and the velocity associated with $\dot{V}O_2$ max ($\dot{v}V\dot{O}_2$ max). Each then performed a second test to determine the maximal time sustained at $\dot{v}V\dot{O}_2$ max before exhaustion ($T_{lim}$). In addition, on separate days each subject performed in a randomized order three intermittent $\dot{v}V\dot{O}_2$ max running sessions. These sessions involved intermittent exercise at velocities representing 100% and 50% of $\dot{V}O_2$ max. The running sessions were termed 30s~30s, 60s~30s, or $\frac{1}{2}T_{lim}$~$\frac{1}{2}T_{lim}$ based on the time (s) spent at 100% of $\dot{V}O_2$ max and then 50% of $\dot{V}O_2$ max. For example, during the 30s~30s session the subjects were required to run at 100% of $\dot{V}O_2$ max for 30 s, followed by 30 s at 50% of $\dot{V}O_2$ max. For each subject the overall time run at $\dot{v}V\dot{O}_2$ max was exactly the same in all three intermittent sessions, equaling $3 \times T_{lim}$.

The 30s~30s session was chosen because it is widely used by the athletes, and also so that it could be compared with the literature since it has been extensively studied (Astrand et al., 1960; Billat, 2000; Billat et al., 2001; Franch et al., 1998; Gorostiaga et al., 1991). The 60s~30s session is also commonly used by the athletes. Although the responses to 2-min intervals have been studied (Astrand et al., 1960; Billat et al., 1996; Franch et al., 1998), there is less information on the $V\dot{O}_2$ responses to 1-min intervals. Finally, the $\frac{1}{2}T_{lim}$~$\frac{1}{2}T_{lim}$ session was chosen to test the hypothesis that the use of a fixed-fraction of time to exhaustion was more valuable (Billat et al., 1996; 1999b; Smith et al., 1999).

During each test the following respiratory gas exchange variables were collected, using a breath-by-breath portable gas analyzer (Cosmed K4b2, Rome, Italy): $\dot{V}O_2$, $\dot{V}CO_2$, pulmonary ventilation (VE), and respiratory exchange ratio (RER). Calibration procedures were performed before each test according to the manufacturer’s recommendations. Heart rate (HR) was recorded by the K4b2 with the athletes wearing a chest belt (Polar Electro, Finland). At the end of the tests, subjects indicated their rating of perceived exertion (RPE) by pointing to the number that corresponded with their perception of effort, based on the 6–20 Borg scale (Borg, 1970). All sessions were performed at the same time of day (±1 hr) to minimize the effects of diurnal variations on the measured variables. Wind velocity was monitored continuously with an anemometer (Alba, Silva, Sweden) and sessions were postponed when wind velocity was >1.5 m·s⁻¹. Subjects trained consistently during the experimental period mainly in swimming, cycling, and running, but they were directed to arrive fully rested for the experimental sessions and to have abstained from caffeine and alcohol in the 24 hrs prior to testing.

**Incremental Test to Exhaustion.** The initial velocity of the test was set at 8 km·h⁻¹ under an estimated achievable $\dot{v}V\dot{O}_2$ max. The test was expected to last approximately 15 min. The increments of velocity were set at 0.5 km·h⁻¹ for 1-min stages. The subjects adjusted their running velocity to auditory signals at 20-m intervals, delimited by visual marks along the track. All were familiar with this procedure as it is used often to set the pace during training sessions. All subjects were encouraged to put forth their best effort. Breath-by-breath data were averaged over 30-s and $\dot{V}O_2$ max was arbitrarily defined as the highest 30-s values reached during the incremental test. $\dot{v}V\dot{O}_2$ max was determined as the minimal velocity at
which \( \dot{V}O_2 \text{max} \) was reached (Billat et al., 1994), calculated as the velocity of the preceding stage completed plus the fraction of time spent in the stage until \( \dot{V}O_2 \text{max} \) was reached multiplied by 0.5 km·h\(^{-1}\).

**Time to Exhaustion at \( \dot{V}O_2 \text{max} \).** Prior to the test, the subjects warmed up for 6 min at 75% \( \dot{V}O_2 \text{max} \) for the determining of net energy cost (\( CR_{75\%} \), ml O\(_2\)-kg\(^{-1}\)-km\(^{-1}\)) at a submaximal intensity. \( CR_{75\%} \) was calculated from \( \dot{V}O_2 \) data averaged during minutes 3 to 4 using the following equation:

\[
CR = (\dot{V}O_2 - 0.083) \times V^{-1}
\]

where \( \dot{V}O_2 \) is expressed in ml·kg\(^{-1}\)·s\(^{-1}\), 0.083 ml·kg\(^{-1}\)·s\(^{-1}\) is the y-intercept of the \( \dot{V}O_2 \)-velocity relationship of young adults, and \( V \) is expressed in m·s\(^{-1}\) (Medbo et al., 1988).

Following a 5-min period of standing rest, subjects exercised to exhaustion at \( \dot{V}O_2 \text{max} \) (\( T_{\text{lim}} \)). During the \( T_{\text{lim}} \) test they maintained velocity constant at \( \dot{V}O_2 \text{max} \) until exhaustion, or until they were stopped because they were more than 1 meter late compared to the expected pace.

**Intermittent Runs.** The first intermittent session, termed 30s~30s, consisted of three sets of \( n \times (30\text{-s run at 100\% } \dot{V}O_2 \text{max} \text{ alternated with 30-s run at 50\% } \dot{V}O_2 \text{max}) \) with \( n = \frac{T_{\text{lim}}}{30\text{ s}} \). The second intermittent session, termed 60s~30s, was composed of three sets of \( n' \times (60\text{-s run at 100\% } \dot{V}O_2 \text{max} \text{ alternated with 30-s run at 50\% } \dot{V}O_2 \text{max}) \) with \( n' = \frac{T_{\text{lim}}}{60\text{ s}} \). A third intermittent session, termed \( \frac{1}{2}T_{\text{lim}}~\frac{1}{2}T_{\text{lim}} \), consisted of three sets of \( 2 \times \left( \frac{1}{2}T_{\text{lim}} \text{ run at 100\% } \dot{V}O_2 \text{max} \text{ alternated with } \frac{1}{2}T_{\text{lim}} \text{ run at 50\% } \dot{V}O_2 \text{max} \right) \). In all the intermittent runs, the recovery between the three sets was passive and lasted 5 min. If \( T_{\text{lim}} \) was not divisible by 30 or 60 s, the duration of the last work-interval of each set was adjusted in order to keep the overall time sustained at \( \dot{V}O_2 \text{max} \) exactly the same in all three intermittent runs. For example, Subject No. 5 (\( T_{\text{lim}} = 285\text{ s} \)) performed in each of the three sets:

- \( 8 \times 30\text{ s} + 1 \times 45\text{ s} \) in 30s~30s;
- \( 4 \times 60\text{ s} + 1 \times 45\text{ s} \) in 60s~30s;
- and \( 2 \times 143\text{ s} \in \frac{1}{2}T_{\text{lim}}~\frac{1}{2}T_{\text{lim}} \).

\( \dot{V}O_2 \text{peak} \) and \( HR\text{peak} \) were defined as the highest 5-s values reached. Times sustained above 95% and 90% of \( \dot{V}O_2 \text{max} \) and \( HR\text{max} \) were compared between the three intermittent sessions.

**Statistical Analysis.** Mean and standard deviations were calculated for all variables. Paired \( t \)-tests were used to determine the significance of differences in the measured variables between the incremental test and the \( T_{\text{lim}} \) test. A one-way repeated measures ANOVA was used to identify differences in \( \dot{V}O_2 \text{peak} \), \( HR\text{peak} \), and RPE between the five running sessions and in the other variables between the three intermittent sessions. Pearson correlation coefficients were used to examine the relationships between \( \dot{V}O_2 \text{max} \), \( \dot{V}O_2 \text{max} \), \( T_{\text{lim}} \), and the time sustained above 95% and 90% of \( \dot{V}O_2 \text{max} \) or \( HR\text{max} \) in the intermittent runs. For all statistical analyses, a \( p \)-value of 0.05 was accepted as the level of statistical significance.

**Results**

The individual results of the incremental running test to exhaustion and the \( \dot{V}O_2 \text{max} \) time to exhaustion (\( T_{\text{lim}} \)) test are listed in Table 1. \( \dot{V}O_2 \text{peak} \), \( HR\text{peak} \), and RPE were significantly lower in 30s~30s than in the other running sessions (Table 2). It
Table 1  Individual Data Measured in Incremental Test and in v\(\dot{V}{O_2}\)max Time-to-Exhaustion Test

<table>
<thead>
<tr>
<th>Subjects</th>
<th>(v\dot{V}{O_2})max (km·h(^{-1}))</th>
<th>(\dot{V}{O_2})max (ml·min(^{-1})·kg(^{-1}))</th>
<th>HRmax (bpm)</th>
<th>RPE (points)</th>
<th>(T_{\text{lim}}) (s)</th>
<th>(\dot{V}{O_2})peak (ml·min(^{-1})·kg(^{-1}))</th>
<th>HRpeak (bpm)</th>
<th>RPE (points)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.3</td>
<td>70.2</td>
<td>170</td>
<td>16</td>
<td>315</td>
<td>71.8</td>
<td>165</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>74.8</td>
<td>198</td>
<td>16</td>
<td>190</td>
<td>72.6</td>
<td>190</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>20.8</td>
<td>72.6</td>
<td>198</td>
<td>15</td>
<td>210</td>
<td>72.8</td>
<td>190</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>19.5</td>
<td>69.7</td>
<td>196</td>
<td>17</td>
<td>255</td>
<td>67.7</td>
<td>192</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>19.2</td>
<td>74.0</td>
<td>192</td>
<td>17</td>
<td>285</td>
<td>72.0</td>
<td>186</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>21.0</td>
<td>73.1</td>
<td>202</td>
<td>16</td>
<td>195</td>
<td>72.3</td>
<td>194</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>20.0</td>
<td>71.6</td>
<td>198</td>
<td>17</td>
<td>180</td>
<td>64.2</td>
<td>190</td>
<td>17</td>
</tr>
<tr>
<td>8</td>
<td>18.4</td>
<td>62.4</td>
<td>188</td>
<td>16</td>
<td>255</td>
<td>62.4</td>
<td>188</td>
<td>16</td>
</tr>
<tr>
<td>Mean</td>
<td>19.9</td>
<td>71.1</td>
<td>192.8</td>
<td>16.3</td>
<td>235.6</td>
<td>69.5</td>
<td>186.9*</td>
<td>15.8</td>
</tr>
<tr>
<td>(SD)</td>
<td>(0.9)</td>
<td>(3.9)</td>
<td>(10.1)</td>
<td>(0.7)</td>
<td>(49.2)</td>
<td>(4.2)</td>
<td>(9.2)</td>
<td>(0.9)</td>
</tr>
</tbody>
</table>

Note: \(v\dot{V}{O_2}\)max = velocity associated with maximal O\(_2\) uptake; \(\dot{V}{O_2}\)max = max 30-s averaged oxygen uptake; HRmax = max 5-s averaged heart rate; RPE = rating of perceived exertion; \(v\dot{V}{O_2}\)peak = max 5-s averaged oxygen uptake; HRpeak = max 5-s averaged heart rate.

\(p < 0.001\) for differences with incremental test.
Table 2 Data (mean ± SD) Measured in Both Tests and the Three Intermittent Running Sessions at v\(\dot{\text{V}}\text{O}_2\text{max}\)

<table>
<thead>
<tr>
<th>Time (s) at</th>
<th>(&gt;95%) (\dot{\text{V}}\text{O}_2\text{max})</th>
<th>(&gt;90%) (\dot{\text{V}}\text{O}_2\text{max})</th>
<th>(&gt;95%) HRmax</th>
<th>(&gt;90%) HRmax</th>
<th>(\text{Averaged End-Intervals } \dot{\text{V}}\text{O}_2) (ml·min(^{-1})·kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1st set</td>
</tr>
<tr>
<td>Incremental test</td>
<td>71.1</td>
<td>192.8</td>
<td>16.3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>T(_{\text{lim}}) test</td>
<td>69.5</td>
<td>186.9 **</td>
<td>15.8</td>
<td>86.1</td>
<td>153.3</td>
</tr>
<tr>
<td>30s~30s</td>
<td>65.4 * †</td>
<td>183.1 ** †</td>
<td>12.4 ** †</td>
<td>54.0</td>
<td>148.6</td>
</tr>
<tr>
<td>60s~30s</td>
<td>71.7 b</td>
<td>188.8 b *</td>
<td>16.0 c</td>
<td>195.9 b</td>
<td>530.8 c</td>
</tr>
<tr>
<td>(\frac{1}{2}) T(<em>{\text{lim}}) ~ (\frac{1}{2}) T(</em>{\text{lim}})</td>
<td>72.2 c</td>
<td>187.0 a **</td>
<td>15.8 b</td>
<td>282.3 b</td>
<td>486.3 c</td>
</tr>
</tbody>
</table>

Note: In every intermittent running session, total time run at v\(\dot{\text{V}}\text{O}_2\text{max}\) was 3 × T\(_{\text{lim}}\) = 706.9 ± 147.7 s. \(\dot{\text{V}}\text{O}_2\text{peak}\) = max 5-s averaged \(\dot{\text{V}}\text{O}_2\) uptake measured in the session; HRmax = max 5-s avgd HR measured in session; RPE = rating of perceived exertion; time at >95% or >90% \(\dot{\text{V}}\text{O}_2\text{max}\) or HRmax = overall time in session spent at 5-s avgd \(\dot{\text{V}}\text{O}_2\) or HR above 95% or 90% \(\dot{\text{V}}\text{O}_2\text{max}\) (expressed in % of T\(_{\text{lim}}\) = time to exhaustion at v\(\dot{\text{V}}\text{O}_2\text{max}\)). Average end-intervals \(\dot{\text{V}}\text{O}_2\) = avg of n, n', or 2 avgd 5-s end-interval values in 1st, 2nd, or 3rd set of intermittent runs. *\(p < 0.05\); **\(p < 0.001\) for diff. w/incremental test. †\(p < 0.05\); ††\(p < 0.001\) for diff. with T\(_{\text{lim}}\) test. Differences between intermittent runs: §\(p < 0.05\); §\(p < 0.01\); †§\(p < 0.001\) for diff. w/30s~30s. Differences in time at %\(\dot{\text{V}}\text{O}_2\text{max}\) or HRmax between intermittent running sessions and T\(_{\text{lim}}\) not tested since overall time run at v\(\dot{\text{V}}\text{O}_2\text{max}\) was threefold higher.
is of interest to note that VO₂peak reached values slightly higher (n.s.) in \( \frac{1}{2} T_{\text{lim}} \) or in 60s~30s than in the incremental test. No differences were observed between 60s~30s and \( \frac{1}{2} T_{\text{lim}} \) in VO₂peak, HRpeak, or RPE. HRpeak was significantly higher in the incremental test than in the other runs.

Times sustained above 95% and 90% of VO₂max are listed in Table 2. Times spent above 95% or 90% of VO₂max were significantly longer either in 60s~30s or \( \frac{1}{2} T_{\text{lim}} \) than in 30s~30s. When expressed as %Tₗₘᵢₙ for comparison between subjects, times above 95% and 90% of VO₂max were, respectively, 23 ± 23% and 63 ± 55% in 30s~30s; 118 ± 63% and 207 ± 60% in 60~30s; and 117 ± 80% and 194 ± 58% in \( \frac{1}{2} T_{\text{lim}} \) (Figure 1). Thus the times sustained above 95% of VO₂max in 60s~30s or \( \frac{1}{2} T_{\text{lim}} \) were longer than the overall time to exhaustion at v_VO₂max in a continuous run (Tₗₘᵢₙ).

As imposed by the experimental protocol, the number of intervals performed in each session was 22.5 ± 4.5 in 30s~30s, 11.3 ± 2.7 in 60s~30s, and 6.0 ± 0.0 in \( \frac{1}{2} T_{\text{lim}} \) and were significantly (p < 0.001) different. The overall number of intervals, in which 95% or 90% of VO₂max was reached, was higher in 60s~30s (respectively, 9.6 ± 3.0 and 11.0 ± 2.3) than in \( \frac{1}{2} T_{\text{lim}} \) (respectively, 5.6 ± 0.5 and 6.0 ± 0.0). There was no difference in number of intervals in which 95% or 90% of VO₂max was reached between 30s~30s and \( \frac{1}{2} T_{\text{lim}} \). Five subjects did not reach 95% of VO₂max in 30s~30s, and no one reached it in 60s~30s or in \( \frac{1}{2} T_{\text{lim}} \). Moreover, three athletes did not reach 95% of HRmax in 30s~30s. The average VO₂ values measured at the end of the intervals in the first, second, and third set did not differ between the three sets within the same intermittent run, but were significantly higher in 60s~30s or in \( \frac{1}{2} T_{\text{lim}} \) than in 30s~30s (Table 2). CR₇₅% measured prior to Tₗₘᵢₙ and the three intermittent running sessions was not different (respectively, 198 ± 17, 192 ± 13, 195 ± 12, and 195 ± 16 ml·kg⁻¹·km⁻¹ for Tₗₘᵢₙ, 30s~30s, 60s~30s, and \( \frac{1}{2} T_{\text{lim}} \)). Likewise, HR₇₅% was similar between these four sessions.

No significant (p > 0.05) relationship was observed between Tₗₘᵢₙ and VO₂max. There was a negative correlation (r = −0.75, p < 0.05) between the time spent above 90% VO₂max in 30s~30s, expressed in %Tₗₘᵢₙ for comparison between subjects, and Tₗₘᵢₙ (Figure 1). Either the difference of time spent over 90% VO₂max between 60s~30s and 30s~30s or between \( \frac{1}{2} T_{\text{lim}} \) and 30s~30s were correlated (respectively, r = 0.77, p < 0.05, and r = 0.97, p < 0.001) with Tₗₘᵢₙ (Figure 2). In other words, the longer the time spent at v_VO₂max before exhaustion (Tₗₘᵢₙ), the shorter the time above 90% of VO₂max in 30s~30s (Figure 1), and the larger the differences in time above 90% of VO₂max between the long-interval intermittent runs and 30s~30s (Figure 2).

**Discussion**

The main results of the present study are that intermittent running sessions with the same overall time run at v_VO₂max but with different work-interval durations led to different VO₂ and HR responses in well-trained athletes. Long-interval intermittent runs were associated with significantly longer times near VO₂max and HRmax than with 30-s work intervals. In addition, time to exhaustion in a continuous run at v_VO₂max (Tₗₘᵢₙ) was correlated to the differences of time sustained at a high percentage of VO₂max between the long- and short-interval sessions.
One could argue that the differences measured between the different sessions could have been caused by the variability in aerobic fitness between subjects or by the variability in measurement errors. Since subjects were well trained and were tested at the same time of day over a short-period, the variability in VO₂ is small (3.4%) (Stuart et al., 1981). In addition, over the experimental period, CR₇₅% and HR₇₅% were kept constant in the submaximal runs performed by all athletes below the second ventilatory threshold (= 86.₃ ± 6.₆% of VO₂max), indicating that the measurement error (calibration, collection, gas leakage, etc.) of the gas analysis system was negligible in the present study.

At the same time, the validity of the system (K₄b₂) used in the present study has already been reported (McLaughlin et al., 2001) but its reliability has never been studied. However, Lucia et al. (1993) showed that the K2 system (the previous version of K4, which did not perform CO₂ analysis) had a variability over three repeated measures that was consistently below 5% across all workloads. One could also argue that the incremental test was too long to elicit maximal VO₂ values. However, since VO2peak values were not different in the incremental test, the Tlim test, the 60s~30s, and ½Tlim~½Tlim sessions, it seems that maximal responses were obtained.

In the present study the mean Tlim was 236±49 s, and it took 150 s to reach 95% of VO₂max allowing the athletes to spend 86 s above 95% of VO₂max. The time to reach 95% of VO₂max is quite similar to values reported in previous studies, e.g., 149 and 166 s (Hill and Rowell, 1997; Hill et al., 1997), but both Tlim and time above 95% of VO₂max are different from the values reported by Hill et al., respectively, 330 and 164 s (Hill et al., 1997), 290 and 140 s (Hill and Rowell, 1997), or by Billat et al. (1999a), respectively, 333 and 190 s. The physiological characteristics of the subjects in the present study may explain the shorter time sustained near or at VO₂max, and thus the shorter time to exhaustion at vVO₂max compared to previous studies. Billat et al. (1994, 1996) demonstrated that in a
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A homogeneous group of elite runners, running time to exhaustion at v\(\text{VO}_2\)max was inversely related to \(\text{VO}_2\)max. Moreover, it has been shown that the significant role of the anaerobic contribution as well as the interindividual variability in \(T_{\text{lim}}\) and in time at \(\text{VO}_2\)max were largely explained by differences in anaerobic capacity (Billat et al., 1994; Hill and Rowell, 1996; Hill et al., 1997).

The triathletes of the present study (track v\(\text{VO}_2\)max = 19.9 ± 0.9 km·h\(^{-1}\); \(\text{VO}_2\)max = 71.1 ml·min\(^{-1}\)·kg\(^{-1}\)) were at a higher fitness level than athletes in the previous studies who had v\(\text{VO}_2\)max = 16.3–17.0 km·h\(^{-1}\) and \(\text{VO}_2\)max = 52.1–61.6 ml·min\(^{-1}\)·kg\(^{-1}\) (Billat et al., 1999a; Hill and Rowell, 1997; Hill et al., 1997). At the same time, the training regimen of subjects in this study mainly consisted of a high volume of aerobic training with relatively low intensity in the three disciplines: swimming, cycling, and running. Gorostiaga et al. (1991) showed that continuous training at low (50% \(\text{VO}_2\)max) intensity produced higher muscle oxidative capacity (muscle citrate synthase activity) but lower increases in \(\text{VO}_2\)max and in maxi-

Figure 2. Relationship between \(T_{\text{lim}}(s)\) and: (A) Difference of time (s) spent over 90% of \(\text{VO}_2\)max between 60s–30s and 30s–30s [Time >90% \(\text{VO}_2\)max 60s–30s – 30s–30s] or (B) Difference of time (s) spent over 90% of \(\text{VO}_2\)max between \(\frac{1}{2}T_{\text{lim}}\)–\(\frac{1}{2}T_{\text{lim}}\) and 30s–30s [Time >90% \(\text{VO}_2\)max \(\frac{1}{2}T_{\text{lim}}\)–\(\frac{1}{2}T_{\text{lim}}\)–30s–30s].
mal exercise capacity than did interval training (30s~30s) at high (100% VO₂max) intensity. Therefore it is not surprising that the time sustained at VO₂max was lower than for middle-distance runners, who probably had a higher anaerobic capacity, even though their competitive level was lower than that of the subjects in the present study.

With the same time run at vVO₂max in the three sessions, the time spent over 95% or 90% of VO₂max was significantly shorter in 30s~30s than in the two longer-interval training sessions (60s~30s and 1 /2 Tlim~1 /2 Tlim, see Table 2). In one of the first studies on metabolic responses to intermittent running, Astrand et al. (1960) showed that during exercise at 98% of the power related to VO₂max, long work periods (2 or 3 min) led to the attainment of VO₂max, in contrast to short work periods (30 s) which resulted in submaximal responses (63% VO₂max). Medbo et al. (1988) pointed out that the amount of oxygen stored in the muscular myoglobin was important (=10% of maximal accumulated oxygen deficit), minimizing the cumulative effects in short intervals.

In addition, it is known that the decline in phosphocreatin e after a brief high-intensity exercise is followed by a fast and almost complete resynthesis in the subsequent recovery period (Simoneau et al., 1987). Moreover, it has been shown that time to exhaustion and time at VO₂max were longer in intermittent runs than in continuous runs at the same velocity (Demarie et al., 2000). These studies, in line with the present one, support the view that if the goal is to sustain a long time at high intensity (≥ 90% VO₂max), the duration of the sets consisting of very short (≤30 s) work intervals must be longer than Tlim. In this case it would be a more effective method for sustaining a greater duration near VO₂max. However, in the present study the average VO₂ measured at the end of the intervals in all three sets did not differ between the three sets within the same intermittent session. One could conclude that the 5-min passive rest between sets was long enough to restore the work capacity in a manner that resulted in the average VO₂ not being elevated during the session.

There were no differences in time spent at an intensity approaching VO₂max between 60s~30s and 1 /2 Tlim~1 /2 Tlim. The use of a fixed fraction, e.g., 50% (Billat et al., 1996; 1999b), >60% (Hill and Rowell, 1997), or between 60 and 75% (Smith et al., 1999) of Tlim was proposed as a way to individualize training prescription, providing greater improvements than in classical fixed-duration interval training. Hill and Rowell (1997) showed that, for a given percentage of Tlim, the time sustained at (or near) VO₂max differed widely among runners; therefore they stated there was no rationale to support the prescribing of the work-interval duration as a fixed percentage of Tlim.

The present results are in line with this view, showing that the use of a fixed-fraction of Tlim does not necessarily lead to greater time at VO₂max than when using a fixed work-interval duration. It took 83 s for the present subjects to reach 90% VO₂max during the Tlim test. Based on the rationale of Hill and Rowell (1997), one could have expected a greater time above 90% VO₂max in 1 /2 Tlim~1 /2 Tlim than in 60~30s since the work-interval duration in the former (118 s) was greater than the time needed to reach 90% VO₂max during the Tlim test (83 s), and greater than the work-interval duration in 60~30s (60 s). However, no differences were observed in time sustained above 90% VO₂max between 60s~30s and 1 /2 Tlim~1 /2 Tlim. This
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finding is in contrast with the main conclusion of Hill and Rowell (1997), that the work duration should at least be of the duration needed in $T_{\text{lim}}$ to reach the intensity ($%\dot{V}O_2\text{max}$) targeted—consequently, at least of 60% of $T_{\text{lim}}$ in their study.

Optimal improvement in aerobic fitness is induced by exercise sustained at 90 to 100% $\dot{V}O_2\text{max}$ (Robinson et al., 1991; Tabata et al., 1997), as well as by the time spent or the distance run at these intensities (Billat, 2001). The present study showing correlations between $T_{\text{lim}}$ and the difference of time spent over 90% $\dot{V}O_2\text{max}$ between 60s~30s and 30s~30s ($r = 0.77, p < 0.05$), or between $\frac{1}{2}T_{\text{lim}}\sim\frac{1}{2}T_{\text{lim}}$ and 30s~30s ($r = 0.97, p < 0.001$), provides data as to the method for determining the most efficient duration of work interval at $\dot{V}O_2\text{max}$. It suggests that athletes with long $T_{\text{lim}}$ would spend significantly less “valuable” time in short work-interval training than would athletes with short $T_{\text{lim}}$. It shows further that athletes with long $T_{\text{lim}}$ will benefit more from long work-interval duration than athletes having a short $T_{\text{lim}}$.

Further studies are needed to determine whether interval training with a personalized fraction of $T_{\text{lim}}$ (i.e., based on the time to reach 90 or 95% $\dot{V}O_2\text{max}$) would result in a most efficient training with longer duration near $\dot{V}O_2\text{max}$. Although defining training characteristics in relation to HR remains a valuable method for prescribing a training regimen, trainers and athletes who cannot usually access a portable gas exchange measurement device would benefit from further studies on the relationships between $\dot{V}O_2\text{max}$, $T_{\text{lim}}$, and the efficiency of different types of intermittent run-training sessions.

In conclusion, comparison of three intermittent runs—30s~30s, 60s~30s, and $\frac{1}{2}T_{\text{lim}}\sim\frac{1}{2}T_{\text{lim}}$—with different work-interval durations but with same overall time run at $\dot{V}O_2\text{max}$, showed that short-interval intermittent running led to shorter time at a high percentage of $\dot{V}O_2\text{max}$. Moreover, athletes with a long $T_{\text{lim}}$ at $\dot{V}O_2\text{max}$ probably required a longer time to reach 90% $\dot{V}O_2\text{max}$, and as a consequence their $\dot{V}O_2$ remained low in the 30s~30s session. Therefore, the differences in time above 90% $\dot{V}O_2\text{max}$ between the long-interval and short-interval intermittent runs were larger. These results confirm that $\dot{V}O_2\text{max}$ and $T_{\text{lim}}$ are useful parameters for setting interval-training sessions when the aim is to exercise near $\dot{V}O_2\text{max}$.

The results also show that athletes who train at $\dot{V}O_2\text{max}$ for a fixed fraction of $T_{\text{lim}}$ do not spend a longer time at $\dot{V}O_2\text{max}$. Therefore, performing intermittent running at $\dot{V}O_2\text{max}$ for a fixed fraction of $T_{\text{lim}}$ may not be the most efficient method. However, athletes with a longer $T_{\text{lim}}$ should use longer work intervals at $\dot{V}O_2\text{max}$. One could suggest that the use of personalized fractions of $T_{\text{lim}}$ as work interval would increase the efficiency of such interval-training sessions. However, further longitudinal studies are required in order to show that training with a personalized fraction would induce a significantly larger improvement than would the other types of intermittent running sessions.

References


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