Interval training at VO$_{2\text{max}}$: effects on aerobic performance and overtraining markers

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ABSTRACT

BILLAT, V. L., B. FLECHET, B. PETIT, G. MURIAUX, and J-P. KORALZSTEIN. Interval training at VO$_{2\text{max}}$: effects on aerobic performance and overtraining markers. Med. Sci. Sports Exerc., Vol. 31, No. 1, pp. 156–163, 1999. Purpose: Between inefficient training and overtraining, an appropriate training stimulus (in terms of intensity and duration) has to be determined in accordance with individual capacities. Interval training at the minimal velocity associated with VO$_{2\text{max}}$ (vVO$_{2\text{max}}$) allows an athlete to run for as long as possible at VO$_{2\text{max}}$. Nevertheless, we don't know the influence of a defined increase in training volume at vVO$_{2\text{max}}$ on aerobic performance, noradrenaline, and heart rate. Methods: Eight subjects performed 4 wk of normal training (NT) with one session per week at vVO$_{2\text{max}}$, i.e., five repetitions run at 50% of the time limit at vVO$_{2\text{max}}$, with recovery of the same duration at 60% vVO$_{2\text{max}}$. They then performed 4 wk of overload training (OT) with three interval training sessions at vVO$_{2\text{max}}$. Results: Normal training significantly improved their velocity associated with VO$_{2\text{max}}$ (20.5 ± 0.7 vs 21.1 ± 0.8 km/h, P = 0.02). As a result of improved running economy (50.6 ± 3.5 vs 47.5 ± 2.4 mL·min$^{-1}$·kg$^{-1}$, P = 0.02), VO$_{2\text{max}}$ was not significantly different (71.6 ± 4.8 vs 72.7 ± 4.8 mL·min$^{-1}$·kg$^{-1}$). Time to exhaustion at vVO$_{2\text{max}}$ was not significantly different (301 ± 56 vs 283 ± 41 s) as was performance (i.e., distance limit run at vVO$_{2\text{max}}$: 2052.2 ± 331 vs 1986.2 ± 252.9 m). Heart rate at 14 km/h decreased significantly after NT (162 ± 16 vs 155 ± 18 bpm, P < 0.01). Lactate threshold remained the same after normal training (84.1 ± 4.8% of vVO$_{2\text{max}}$). Overload training changed neither the performance nor the factors concerning performance. However, the submaximal heart rate measured at 14 km/h decreased after overload training (155 ± 18 vs 150 ± 15 bpm). The maximal heart rate was not significantly different after NT and OT (199 ± 9.5, 198 ± 11, 194 ± 10.4, P = 0.1). Resting plasma norepinephrine (venous blood sample measured by high pressure liquid chromatography), was unchanged (2.6 vs 2.4 nmol·L$^{-1}$, P = 0.8). However, plasma norepinephrine measured at the end of the vVO$_{2\text{max}}$ test increased significantly (11.1 vs 26.0 nmol·L$^{-1}$, P = 0.002). Conclusion: Performance and aerobic factors associated with the performance were not altered by the 4 wk of intensive training at vVO$_{2\text{max}}$ despite the increase of plasma noradrenaline. Key Words: DISTANCE RUNNING PERFORMANCE, OVERLOAD TRAINING, MAXIMAL OXYGEN CONSUMPTION, NOREPI-NEPHRINE, OVERTRAINING

O vertraining, which is characterized by an athlete's incapacity to perform at his/her previously demonstrated optimum despite maintenance of intensive training, may be caused by an inappropriate use of high-intensity interval training. To calibrate the intensity of interval training, coaches often refer to the velocity associated with the achievement of VO$_{2\text{max}}$ during an incremental treadmill test (vVO$_{2\text{max}}$) and to the velocity at the onset of blood lactate accumulation (VOBLA), both of which have been reported to be good indicators of performance in middle- and long-distance running events (1,5,7,16,23,34). However, the duration of hard work is not individualized (2). Although optimum improvement in cardio respiratory fitness is thought to occur when training at an intensity corresponding to 90–100% of VO$_{2\text{max}}$ (33), the duration of effort is very variable among authors and trainers, from 30 s to 3 min and is never referenced to individual capabilities to sustain high intensity training (time to exhaustion at vVO$_{2\text{max}}$).

The athlete's time to exhaustion at vVO$_{2\text{max}}$ (limvVO$_{2\text{max}}$), has been shown to be reproducible, has been reported as being very different among runners with the same vVO$_{2\text{max}}$ and as being a good parameter of middle-distance performance (6,8). Accordingly, limvVO$_{2\text{max}}$ has been reported to be useful for choosing the duration of interval training (9). Intermittent exercise training stimulus was standardized by alternating periods equal to 50% of tim at vVO$_{2\text{max}}$, with equal durations of recovery at 60% of vVO$_{2\text{max}}$ (work:rest = 1:1). With this procedure, despite the large individual range of timvVO$_{2\text{max}}$, the total time at vVO$_{2\text{max}}$ will be 2 to 2 ½ times the continuous tim 100 (9). Following the same reasoning, Urhausen et al. (36) considered that exercise, performed at an intensity at about
Figure 1—Experimental schedule design.

10% above the maximal lactate steady state, could be regarded as useful for an examination of exercise-induced hormonal concentrations during overtraining. In this context, the exercise time till exhaustion during this test turned out to be a sensitive single criterion for the diagnosis of overtraining (36). Similarly, tlim\(\text{VO}_{\text{2max}}\) could be used to calibrate length of interval training and could be an exercise model for examining the possible presence of overtraining.

The purpose of this investigation was to study the effect of normal and overload interval training at \(\text{vVO}_{\text{2max}}\) on aerobic parameters and overtraining markers such as the plasma norepinephrine and subjective ratings of fatigue, stress, muscle soreness, and sleep. We hypothesized that the calibration of interval training with the individual time to exhaustion at \(\text{vVO}_{\text{2max}}\) could induce a rapid increase of \(\text{vVO}_{\text{2max}}\) using only one weekly session for 4 wk. Moreover, we thought that the calibration of length of interval training at \(\text{vVO}_{\text{2max}}\). In reference to tlim\(\text{VO}_{\text{2max}}\), could allow for the number of these individual training sessions (at \(\text{vVO}_{\text{2max}}\)) to increase without inducing overtraining syndrome. Indeed, during the 2 months of the precompetitive macrocycle, it is usual for trainers to overload interval training at a velocity close to \(\text{vVO}_{\text{2max}}\) with a hard mesocycle of 4 wk, achieving three training session per week rather than one or two (3,4). This is why this study has the special purpose of examining the effects of such overload interval training at \(\text{vVO}_{\text{2max}}\) (three sessions of interval training at \(\text{vVO}_{\text{2max}}\) + one session run at the velocity associated with the onset of blood lactate accumulation, vOBLA, per week), coming after 4 wk of normal training (one session of interval training at \(\text{vVO}_{\text{2max}}\) + one session of OBLA training per week).

METHODS

Subjects. Eight endurance-trained male athletes volunteered to participate in this study. These athletes specialized in middle and long-distance running (1500 m to half-marathon). They were of mean (±SD) age 24 ± 3.2, height 175.0 ± 3.3 cm, and weight 65.0 ± 4.5 kg. Before participation, all subjects provided voluntary written informed consent in accordance with the guidelines of the Université de Paris. Figure 1 describes the experimental design over 11 wk, and Table 1 gives an example of weekly programs for prebaseline, normal, and overload training for a subject having a \(\text{vVO}_{\text{2max}}\) of 21 km h\(^{-1}\) on a treadmill, an onset of blood lactate accumulation velocity (vOBLA) equal to 18 km h\(^{-1}\) (85% of \(\text{vVO}_{\text{2max}}\)) and a time to exhaustion at \(\text{vVO}_{\text{2max}}\) equal to 6 min. All the tests were performed three times, once before and after normal training period and once after overload training at \(\text{vVO}_{\text{2max}}\).

Therefore, in weeks 1, 6, and 11, subjects performed an incremented 0%–slope treadmill test to exhaustion for the determination of \(\text{tlim\text{VO}}_{\text{2max}}\), \(\text{vVO}_{\text{2max}}\) and the velocity that elicits 4 mM of blood lactate concentration (OBLA) (34), and an all-out run at \(\text{vVO}_{\text{2max}}\) to determine tlim\(\text{VO}_{\text{2max}}\). Subjects performed only one test on any given day, and tests were each separated by ≥48 h but completed within the period of 1 wk, during which training was kept relatively constant. All treadmill tests were performed at the same time of day (between 10:00 h and 16:00 h) in a climate-controlled (21–22°C) laboratory. Subjects were ordered to be rested when they reported to the track or laboratory and not to train hard or eat or ingest beverages containing caffeine before testing. All training sessions were performed on track, road, and field for 8 wk.

Data Collection Procedures

Determination of \(\text{VO}_{\text{2max}}\) and \(\text{vVO}_{\text{2max}}\) laboratory tests. All of the runs were on a level treadmill, a Gymrol 1800 treadmill (Techmachine, Saint Etienne, France) with speed controlled at a precision of 0.5 m s\(^{-1}\). The speed controller was developed for use in this laboratory by Le Centre d’Enseignement et de Développement pour le Montage en Surface (Université Joseph Fourier, Grenoble, France).

Initial treadmill speed was 10 km h\(^{-1}\) with a 0% slope. Subjects performed at stages of 3-min, and the speed was increased of 1 km h\(^{-1}\) every 3 min without any pauses in between. When respiratory exchange ratio (RER) had reached 1.00, stages were shortened to 2 min and increments to 1 km h\(^{-1}\). Cardiorespiratory-metabolic variables were measured using an EOS-Sprint automated metabolic cart (Jaeger, Würzburg, Germany) and a MAX-1 electrocardiograph (Marquette Electronics, Milwaukee, WI). The metabolic cart was calibrated before each test according to the manufacturer’s instructions. 15-s averages for \(\text{VO}_2\), \(\text{VCO}_2\), VE, VE/\(\text{VO}_2\), RER, and heart rate (HR) were calculated. The highest 15-s value for \(\text{VO}_2\) was recorded as maximal \(\text{VO}_2\); values for \(\text{VCO}_2\), VE, VE/\(\text{VO}_2\), RER, and HR from the 15-s period when \(\text{VO}_{2max}\) occurred were recorded as the maximal values for these variables.

\(\text{VO}_{2max}\) was the minimal speed at which the athlete was running when \(\text{VO}_{2max}\) occurred, as long as this speed was sustained for at least 1 min. If an athlete achieved \(\text{VO}_{2max}\) during a stage that was not sustained for 1 min, the speed of the previous stage was recorded as \(\text{vVO}_{2max}\).

Determination of tlim at \(\text{vVO}_{2max}\). Subjects began with a 15-min warm-up at 60% of \(\text{vVO}_{2max}\) to determine tlim at \(\text{vVO}_{2max}\). Subjects then continued to run as the treadmill speed was increased in ramp fashion over a 30- to
TABLE 1. Baseline, normal, and overload interval training programs.

<table>
<thead>
<tr>
<th>Days</th>
<th>Baseline Training (performed at minimum during 2 yr before the experiment)</th>
<th>Normal training ([week 2 → week 5])</th>
<th>Overload training ([week 6 → week 10])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>1 h of easy run (12 km·h⁻¹) Σ = 12 km</td>
<td>1 hour of easy run at 60% VO₂max (12 km·h⁻¹) Σ = 12 km</td>
<td>Interval training 5 × 1050 m in 3 min at VO₂max with 3 min of rest in between (500 m) at 50% VO₂max. Warm-up (4 km) + warm-down (2 km) = 6 km Σ = 14 km</td>
</tr>
<tr>
<td>Tuesday</td>
<td>90 min of easy run (12 km·h⁻¹) Σ = 18 km</td>
<td>interval training 5 × 50% of tlimVO₂max (1000 m in 3 min at VO₂max) with 3 min of rest in between (500 m) at 50% VO₂max. Warm-up (4 km) + warm-down (2 km) = 6 km Σ = 14 km</td>
<td>45 min of easy run at 70% VO₂max (14.7 km·h⁻¹) Σ = 11 km</td>
</tr>
<tr>
<td>Wednesday</td>
<td>45 min of easy run faster than on Monday and Tuesday (14 km·h⁻¹) Σ = 11 km</td>
<td>45 min of easy run at 70% VO₂max (14 km·h⁻¹) Σ = 10.6 km</td>
<td>Interval training as on Monday Σ = 14 km</td>
</tr>
<tr>
<td>Thursday</td>
<td>90 min of easy run (as on Monday and Tuesday) (12 km·h⁻¹) Σ = 18 km</td>
<td>60 min of easy run at 70% VO₂max (14 km·h⁻¹) Σ = 14 km</td>
<td>60 min of easy run at 60% VO₂max (14 km·h⁻¹) Σ = 12.6 km</td>
</tr>
<tr>
<td>Friday</td>
<td>45 min of easy run faster than on Monday and Tuesday (14 km·h⁻¹) Σ = 11 km</td>
<td>2 × 20 min at vOBLA (85% of VO₂max = 17.5 km·h⁻¹) (5660 m) with 5 min of easy run at 60% VO₂max in between (800 m) Σ = 18 km</td>
<td>Interval training as on Monday Σ = 14 km</td>
</tr>
<tr>
<td>Saturday</td>
<td>Rest Σ = 0 km</td>
<td>Rest Σ = 0 km</td>
<td>Rest Σ = 0 km</td>
</tr>
<tr>
<td>Sunday</td>
<td>90 min of easy run (as Monday and Tuesday) (12 km·h⁻¹) Σ = 18 km</td>
<td>60 min of easy run at 70% VO₂max (14 km·h⁻¹) Σ = 14 km</td>
<td>2 × 20 min at vOBLA (85% of VO₂max = 18 km·h⁻¹) (5800 m) with 5 min of easy run at 60% VO₂max in between (800 m) Σ = 19 km</td>
</tr>
<tr>
<td>Total</td>
<td>0 interval training session at VO₂max</td>
<td>1 interval training session at VO₂max</td>
<td>3 interval training session at VO₂max</td>
</tr>
<tr>
<td></td>
<td>0 OBLA training session (85% VO₂max)</td>
<td>1 OBLA training session (85% VO₂max)</td>
<td>1 OBLA training session (85% VO₂max)</td>
</tr>
<tr>
<td></td>
<td>6 training sessions per week</td>
<td>5 training sessions per week</td>
<td>6 training sessions per week</td>
</tr>
<tr>
<td></td>
<td>Σ = 85–90 km</td>
<td>Σ = 85 km</td>
<td>Σ = 85 km</td>
</tr>
</tbody>
</table>

Example for one subject having on treadmill a VO₂max = 22 km·h⁻¹ and time to exhaustion at VO₂max = 6 min before normal training and VO₂max = 21 km·h⁻¹ and time to exhaustion at VO₂max = 6 min after normal training (before overload training). For training on track values of VO₂max are decreased of 1 km·h⁻¹ compared with the treadmill.

45-s period up to VO₂max. When the treadmill speed equalled VO₂max, the stopwatch was started. Subjects were verbally encouraged to continue for as long as possible. A test was terminated when the subject grasped the handrails for support and/or straddled the moving belt. Time was recorded to the nearest second.

**Determination of running economy.** Before the tlimVO₂max tests, runners warmed up at 12 km·h⁻¹ for 7 min, rested for 3 min, and then ran for 8 min at 14 km·h⁻¹ VO₂max (mL·min⁻¹·kg⁻¹) was averaged between the 6th and 7th min at 14 km·h⁻¹ and taken as reference for an athlete’s running economy (RE). RE was defined as being the rate of VO₂ at a given submaximal running velocity by Cavanagh and Williams (12).

**Data collection during laboratory tests.** A fingertip puncture was made before exercise and a blood sample was obtained for immediate analysis of blood lactate concentration, YSI model 27 (Yellow Springs Instruments, Yellow Springs, OH), during the last 30 s of every stage during the tests and after 8 min of seated recovery. Maximal value of blood lactate obtained was recorded as the maximal value of the test. Plasma norepinephrine was measured from venous blood samples measured by high pressure liquid chromatography during rest and at the end of tlimVO₂max.

**Training Protocol (Interval Training at vVO₂max)**

During interval training, the duration of hard runs and recoveries was 50% of the subject’s continuous tlim 100, the total time at 100% of vVO₂max. The intermittent exercise was run at 100% vVO₂max for hard runs and 60% vVO₂max for light runs; the duration ratio was (1:1). In accordance with previous work having shown that, despite a wide range of time to exhaustion at vVO₂max, runners were able to complete five intervals described above (8).

**Training Programs**

The prebaseline, normal, and overload training protocol is summarized on Table 2. Runners had six training sessions per week for both of normal and overload trainings. The normal training week was composed of one running session at the OBLA velocity (twice 20 min with 5 min of rest between the two runs at 40% of vVO₂max pace). Subjects ran four sessions slower than their OBLA velocity. During the overload training (OT) week, the interval training (InTR) at vVO₂max was multiplied by three, with the two InTR added instead of two easy runs at 60–70% of vVO₂max. OBLA training was the same during NT and OT periods. Total kilometrage was not different between the two training periods (85 ± 5 km).

**Training Logs**

**Training instructions.** Velocity associated with VO₂max on a treadmill (0% slope) was assumed to be 1 km·h⁻¹ higher than vVO₂max on track (for training sessions), because of difference in air-resistance (31). This was the same for OBLA velocity. This was in accordance with
other previous experimental data (10,24). Time to exhaustion at \( \text{vVO}_{2\text{max}} \) has been shown to be not significantly different than those on treadmill (10).

For instance, for an interval training session at \( \text{vVO}_{2\text{max}} \), a runner who had a \( \text{vVO}_{2\text{max}} \) on a treadmill equal to 21 \( \text{km} \cdot \text{h}^{-1} \), OBLA velocity of 18 \( \text{km} \cdot \text{h}^{-1} \) and a time to exhaustion at \( \text{vVO}_{2\text{max}} \) equal to 6 min had been considered. Therefore he had to run interval training at 20 \( \text{km} \cdot \text{h}^{-1} \) over half of the distance limit at \( \text{vVO}_{2\text{max}} \), i.e., time to exhaustion \( \times \text{vVO}_{2\text{max}} = 6 \text{ min} \times 20 \text{ km} \cdot \text{h}^{-1} = 2000 \text{ m. Consequently, this runner had to repeat 5 \times 50\% of 2000 = 5 \times 1000} \text{ m at 20 km} \cdot \text{h}^{-1} \text{ on track with an easy run \( (50\% \) of \( \text{vVO}_{2\text{max}} \) of the same duration in between; therefore, during recovery this runner covered half of the distance covered in a hard run \( (500 \text{ m in that example) Before each interval training run at \( \text{vVO}_{2\text{max}} \) and OBLA velocity, the subject warmed up for 4 km and warmed down for 2 km at 60% of \( \text{vVO}_{2\text{max}} \). Each training session was controlled by a professional trainer to be sure that pace was respected.

**Subjective ratings of well-being and heart rate at the awakening.** Runners completed daily training logs upon rising in the morning for the 8 wk of training (normal and overload training). Logs were collected every week. Subjects recorded subjective ratings of quality of sleep, fatigue, stress, and muscle soreness on a scale of 1–7 from very very low or good (point 1) to very very high or bad (point 7) in accordance with Hooper et al. (20). Body mass, early morning heart rate (EMHR: pulse counted on waking while still lying in bed), and the weather for training conditions, were also recorded.

**Data Analyses**

The subjective ratings of well-being were considered equivalent to interval data, particularly considering that there were few values obtained at the extreme ends of the scale. Daily measures of body mass, EMHR, and well-being in the logs were averaged for each training session and compared: normal training (NT) versus overload training (OT).

For data analysis, the submaximal (at 14 \( \text{km} \cdot \text{h}^{-1} \)) and maximal heart rate (at \( \text{vVO}_{2\text{max}} \)) as well as the submaximal values of \( \text{VO}_{2} \) (running economy at 14 \( \text{km} \cdot \text{h}^{-1} \)) were used from the incremental and all-out run at \( \text{vVO}_{2\text{max}} \). All aerobic characteristics and parameters of overtraining were compared with ANOVA for repeated measurements. **Post-hoc** testing was performed by Fischer’s least significant difference test. In addition correlations between all pairs of values and maximal responses were calculated. The level of significance was set at 0.05 and data reported as mean and SD.

**RESULTS**

**Aerobic parameters and tim \( \text{vVO}_{2\text{max}} \).** Table 2 summarizes NT and OT effects on aerobic parameters. A significant increase of \( \text{VO}_{2\text{max}} \) produced by the NT can be underlined. NT produced as a significant increase of \( \text{vVO}_{2\text{max}} \) but no significant change in \( \text{VO}_{2\text{max}} \). There was a significant decrease of the running economy; however, this improvement was not correlated with the increase of \( \text{vVO}_{2\text{max}} \) \((r = -0.393, P = 0.33)\). Moreover, heart rate at 14 \( \text{km} \cdot \text{h}^{-1} \) decreased significantly after each period of training. Despite the increase of velocity associated at \( \text{vVO}_{2\text{max}} \), time to exhaustion at this new \( \text{vVO}_{2\text{max}} \) did not drop significantly after NT and OT. OT did not change \( \text{vVO}_{2\text{max}} \), and runners kept the benefit of normal training. However, the continuing improvement of running economy has underlined the fact that the improvement of RE is dissociated from the increase of \( \text{vVO}_{2\text{max}} \). Heart rate at 14 \( \text{km} \cdot \text{h}^{-1} \) continued to decrease significantly. The drop in heart rate at 14 \( \text{km} / \text{h} \) (AHR) was not correlated with the improvement of running economy (\( \Delta \text{RE} \) either after NT or after OT \((r = 0.41, P = 0.3) \) and \( r = 0.07, P = 0.8 \), respectively). Maximal heart rate, blood
lactate (obtained at the end of incremental test), and OBLA velocity did not change significantly throughout the 8 wk of training.

**Plasma norepinephrine.** Plasma norepinephrine measured at the end of all-out run at \( v\text{VO}_{2\text{max}} \) increased significantly from NT to OT (11.2 ± 6.8 vs 26.0 ± 9.2 nmL\(^{-1}\); \( P = 0.002 \)). Norepinephrine at rest was unchanged (2.6 vs 2.4 nmL\(^{-1}\), \( P = 0.8 \)).

**Subjective ratings of well-being.** Figure 2 shows the evolution of subjective ratings of well-being. The four subjective ratings of well being averaged for NT were not significantly different (2 ± 0.3, 2 ± 0.4, 1.5 ± 0.3, and 2.2 ± 0.2 for muscle soreness, quality of sleep, stress, and fatigue, respectively). Values registered during OT were under 3.5 (scale 1–7), which means that the stress was significantly lower than the other subjective markers of overtraining. Indeed 3.5 is far under the threshold of the overtraining syndrome fixed by Hooper et al. (20) (5 for more than 7 d consecutively). However, subjective ratings of muscle soreness increased significantly from NT to OT (2 ± 0.5 to 3 ± 0.7, \( P = 0.03 \)). This was the same for ratings of quality of sleep (2 ± 0.5 to 3 ± 0.8, \( P = 0.04 \)).

The main finding of this study is that NT including one weekly session of 2 × 20 min (5 min of easy jog in between) and one weekly session of 5 × 50% of tim\( v\text{VO}_{2\text{max}} \) (50% tim at \( v\text{VO}_{2\text{max}} \) of easy jog between) increased \( v\text{VO}_{2\text{max}} \) and OBLA velocity and decreased submaximal heart rate significantly. Moreover, OT at \( v\text{VO}_{2\text{max}} \) did not lead to a performance decrease such as might be expected with overtraining syndrome, but it did not induce an additional improvement of aerobic capacity despite a decrease of submaximal heart rate. It seems that in spite of the increase of training intensity by training at \( v\text{VO}_{2\text{max}} \), instead of two easy runs, the recovery has not been compromised to the point of inducing overtraining syndrome. However, the increase of plasma epinephrine at the end of tim\( v\text{VO}_{2\text{max}} \) and increase in the muscle soreness as well as bad quality of sleep may suggest that the OT compromises the complete restoration of homeostasis between training sessions.

**DISCUSSION**

For the purpose of this study, we hypothesized that individual velocity and duration calibration of interval training after 1 month of normal training could allow overload training at \( v\text{VO}_{2\text{max}} \) for 1 month (with three interval training sessions per week) without inducing overtraining syndrome. To test this hypothesis, we examined the effect of a normal and overload interval training at \( v\text{VO}_{2\text{max}} \) on aerobic parameters and overtraining markers such as the plasma norepinephrine and subjective ratings of fatigue, stress, muscle soreness, and sleep. Indeed, overtraining syndrome is often provoked by daily high-intensity interval training with little recovery between repetitions (22), which seems to be very stressful for the body. Therefore, in the present study, an individual calibration of interval training based on \( v\text{VO}_{2\text{max}} \) and tim\( v\text{VO}_{2\text{max}} \) (for duration) hypothetically might prevent athlete from overtraining.

**Normal and overload interval training effect at \( v\text{VO}_{2\text{max}} \) on aerobic parameters of performance.** By use of this procedure of interval training calibration, but one session per week only (normal training) produced a significant improvement of \( v\text{VO}_{2\text{max}} \) and a significant decrease of the running economy of 10% each, with these two improvement not covarying. Maximal oxygen uptake was constant throughout the 11 wk of experiments.

Regarding the effects of training on RE, some studies reported no differences in RE as a result of training, whereas others found an improvement of running economy, i.e., a decrease of \( \text{VO}_{2} \) at submaximal velocity (21,37) or an increase (13,29,32). As speculated by Daniels (14), it is possible that there may be a certain threshold of training or a particular type of training necessary for inducing a significant change in running economy. The increase of muscle elasticity is believed to be a main mechanism through which running economy can improve (11,12). However, it may be noticed that alterations in training status (increase of \( v\text{VO}_{2\text{max}} \) and \( \text{VO}_{2} \) at the OBLA) may precipitate changes in variables that affect the running economy both positively and negatively. For example, an enhanced training regimen may favorably change running economy by improving muscle elasticity and intracellular oxidative capacity. Conversely, an enhanced training regimen could also reduce running economy by increasing mass distribution of the limbs and increasing \( v\text{VO}_{2\text{max}} \). A greater \( v\text{VO}_{2\text{max}} \) may reduce running economy by increasing the percentage of fat oxidized for energy production at a given running speed. For instance, in Ramsbottom’s et al. study (32), 12 active male undergraduates, significantly improved their running economy from 45.0 ± 3.4 mL·min\(^{-1}\)·kg\(^{-1}\) to 43.3 ± 3.2 after 5 wk of additional endurance in addition to their usual recreational sports. The improvement of times over 5 km were significantly correlated with changes in the running economy at 3.58 m·s\(^{-1}\) (\( r = -0.71, P < 0.01 \)), rather than to changes in the \( v\text{VO}_{2\text{max}} \) (\( r = -0.07; \text{NS} \)). That means that the increase of velocity at 4.30 m·s\(^{-1}\) (maximal velocity over 5 km) covaries with the oxygen consumption at 83% of this velocity showing the increase in aerobic metabolism. For trained runners, it may be possible that an improvement of performance is due rather to the increase of economy and to a decrease of oxygen consumption at submaximal velocities. During this study, \( v\text{VO}_{2\text{max}} \) remained stable as RE improved and consequently \( v\text{VO}_{2\text{max}} \) increased. The change in RE

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was not correlated with those of HR (r = 0.071, P = 0.867). However, the explanation for RE improvement is out of the scope of this study and further research is still necessary to specify the mechanisms of running economy improvements (15,30).

The second point we have to discuss is the absence of VO2max improvement found during this present study. In trained runners (training distance = 82 ± 13 km), Mikesell and Dudley (28) found a significant increase in VO2max using six training sessions per week for 6 wk. However, subjects had extreme difficulty in completing the 6th wk of training (3 d wk⁻¹) they ran as fast as possible for 40 min and on alternate days the subjects performed five 5-min rides on a cycle ergometer at VO2max separated by 5-min intervals of jogging. Therefore Mikesell and Dudley (28) suggested that training at such intensities on a regular basis was not recommended because of the probable reduction in VO2max (58.4 mL.min⁻¹.kg⁻¹ vs 65.0 mL.min⁻¹.kg⁻¹). Otherwise, some studies performed on larger groups obtained a significant increase of VO2max using short high-power or low-power output interval training in well-endurance trained subjects, providing that average power output is above 80% of VO2max (i.e., above the OBLA velocity). For instance, Overend et al. (29) compared three training programs in untrained males for 10 wk (four 40-min sessions a week): 1) continuous training for 40 min; 2) long interval training on a cycle ergometer for 3 min at 100% of power output associated with VO2max (pVO2max) alternated with 2 min at 50%; and 3) short interval training (30 s at 120% of VO2max alternated with 30 s at 40%). Thus, in this design the average power output (and total work) of the interval training program was equated to observe differences related to type of training with average intensity and duration held constant. All three training programs produced a training effect by an increase in VO2max (3.3 to 3.7 L.min⁻¹). This VO2max increase of 12%, obtained in 10 wk and only 40 training sessions, was not found in trained endurance athletes. During this study, work efficiency (determined over the linear period of increase in VO2) did not change.

One other significant finding of the present study is that despite the increase of in vVO2max, tim this at new vVO2max was not significantly less than after normal training. Taking the same absolute speed as reference, Flynn et al. (18) found that after 3 wk of hard training (110 km wk⁻¹) with a 30% of high-intensity training (that represented an increase of 30% in the mileage run at high intensity), eight male collegiate cross-country runners significantly increased their time to exhaustion at 110% of their preseason vVO2max (408.3 ± 41.4 s vs 329.4 ± 31.6 s). Unfortunately, no vVO2max modification has been reported. At least weight has not been modified; however, no conclusion has been set concerning the possible explanation of the endurance increase at 110% of vVO2max preseason. We can hypothesize that subjects ran only at 100% of vVO2max if we consider time to exhaustion (408 s), which is close to those currently found at vVO2max (thus, vVO2max would have been increase by 10%). Flynn et al. (18) reported significant decreases of blood lactate and heart rate (4.3 ± 0.7 vs 9.1 ± 1.3 mM and 154.7 ± 3.4 vs 158.9 ± 3.5 bpm) at 75% of preseason vVO2max. However, this experiment has examined the effects of changes of both training volume and intensity, which makes it difficult to conclude on the particular influence of interval training.

Despite the fact that timvVO2max decreased a little at the new vVO2max and their vVO2max increased significantly, athletes were not able to cover more distance at vVO2max. This shows the importance of timvVO2max in the choice of distance for interval training at vVO2max. Indeed, during the precompetitive macrocycle, it may be possible that athletes increase their vVO2max without sufficiently increasing their tim at vVO2max (this was the case in the present study). OT did not change vVO2max, and runners kept the benefit of normal training. timvVO2max decreased, but not significantly, after OT (Table 2).

OBLA velocity did not significantly change; however, the training at OBLA was maintained at a constant. Before the beginning of normal interval training in the precompetitive macrocycle, athletes ran at their OBLA velocity once a week. Therefore, this training at OBLA did not change significantly throughout the 8 wk of interval training. Absolute velocity of OBLA increased slightly (+0.2 and then +0.4 km h⁻¹ after NT and OT, respectively), but not significantly, and the fraction of VO2max used at OBLA was unchanged (about 85% of VO2max). These runners have high values of OBLA (in % VO2max), and we could suggest that they practice interval training more to increase their performance by increasing their vVO2max.

Normal and overload interval training effect at vVO2max on heart rate and catecholamines. Even though maximal heart rate and blood lactate (obtained at the end of all out run at vVO2max) did not change significantly throughout the 8 wk of training, heart rate at 14 km h⁻¹ decreased significantly after each period of training. With OT, HR at 14 km h⁻¹ continued to decrease significantly. Morning and resting heart rate did not change significantly after NT and OT. Morning and resting heart rate are the most common index of training stress. Resting heart rate could presumably be increased due to increased sympathetic outflow from intense training. Indeed, a significant elevation in the resting heart has been reported after 2 wk of intense field training and successive days of competitive running (17). Another study (18) reported no significant changes in resting heart rate after 3 wk of intensity and volume training increase (described above). In the same way and in accordance with that present study, Kirwan et al. (21) have reported unchanged morning heart rate in competition swimmers who swam twice their normal training volume for 10 d. Resting heart rate was also reported to be somewhat reduced in well-trained distance runners during a brief period of intensified training (21).

This study showed that adding interval training at vVO2max, three times instead of once a week induced a great elevation of plasma norepinephrine measured at the end of the all-out run at vVO2max, which is recognized as an overtraining marker (36). Norepinephrine at rest was unchanged. These all-out run at vVO2max concentrations are comparable.
with those reported in previous studies where the overtraining had been obtained and athletes were no longer able to follow the training overload program (19,25). Indeed, the measurement of plasma noradrenaline levels can provide an indicator of the sympathetic nervous system. Indeed, the catecholamines, both as a neurotransmitter and as a hormone, have very powerful regulatory properties that have control over a number of critical physiological and metabolic functions that are connected with the ability to sustain exercise.

The sympathicoadrenal responses to an acute bout of exercise as well as a result of chronic endurance training are complex (27). This response can vary greatly depending on exercise intensity, duration, type of tissue, and training status of the individual. If the exercise intensity exceeds the individual anoxic threshold by 5% or more leading to an accumulation of blood lactate at the same time, there is an overproportional time and intensity dependent rise in catecholamines as a sign of an increased sympathoadrenergic activation (35). Involvement of the catecholamines is essential in helping the body adjust to the stress of exercise, as they contribute to a number of critical processors including glycogenolysis, glucose uptake, gluconeogenesis, muscle and adipose lypolysis, contractility, inotropic and chronotropic responses of the heart, and circulatory adjustments. Increased blood levels of catecholamines have been reported after exercise in overtrained athletes (20,26).

REFERENCES


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