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Interval Training for Performance: A Scientific and Empirical Practice

Special Recommendations for Middle- and Long-Distance Running. Part I: Aerobic Interval Training

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Abstract

This article traces the history of scientific and empirical interval training. Scientific research has shed some light on the choice of intensity, work duration and rest periods in so-called 'interval training'. Interval training involves repeated short to long bouts of rather high intensity exercise (equal or superior to maximal lactate steady-state velocity) interspersed with recovery periods (light exercise or rest). Interval training was first described by Reindell and Roskamm and was popularised in the 1950s by the Olympic champion, Emil Zatopek.

Since then middle- and long- distance runners have used this technique to train at velocities close to their own specific competition velocity. In fact, trainers have used specific velocities from 800 to 5000m to calibrate interval training without taking into account physiological markers. However, outside of the competition season it seems better to refer to the velocities associated with particular physiological responses in the range from maximal lactate steady state to the absolute maximal velocity. The range of velocities used in a race must be taken into consideration, since even world records are not run at a constant pace.

1. Definition and Characteristics of Interval Training

Training can be defined as the systematic and regular participation in exercise to enhance sports performance. Performance, especially for sports based on locomotion (action to move from one point to another), can be a time to cover a distance (14 minutes over 5000m is a performance) or a distance covered in a time (21km in an hour of running). If one considers the velocity-time relationship, the purpose of training is to shift the curve to the right; to be able to run faster over the same distance or to run a longer time at a given velocity. To date, sports scientists have focused much of their effort on explaining why the accepted training practices result in an enhanced performance. Far less frequently have 'scientific breakthroughs', arising from the laboratory, precipitated major changes in accepted training practices.[1] However, scientific research has shed some light on the choice of intensity, work duration and rest periods in so-called 'interval training'. Interval training involves repeated short to long bouts of rather high intensity exercise (equal or superior to maximal lactate steady-state velocity) interspersed with recovery periods (light exercise or rest). Interval training was first described, in a scientific journal, by Reindell and Roskamm,[2] and Reindell et al.,[3] and was popularised in the 1950s by the Olympic champion, Emil Zatopek.

Since then middle- and long-distance runners have used this technique to train at velocities close to their own specific competition velocity.

Indeed, interval training has a very long tradition. Often cross-country running (and skiing) was included in the training with running (skiing) on the flat, uphills, and downhills, and it was termed ‘natural interval training’. In this kind of interval training the athletes often guided their speed with a stop-watch (e.g. the Swedish runner, Gunder Hägg who in early 1940 achieved 15 individual world records in middle- and long- distance running). The problem was that these training programmes were not published in scientific journals. Interval training, including measurements of heart rate, oxygen uptake ($\dot{V}O_2$) and blood lactate levels, was applied to the successful Swedish cross-country skiers in the 1950s. At that time, it was already known that for a given distance, which at maximal speed took 4.0 minutes to cover, could be prolonged to 4 minutes 30 seconds and still load the oxygen transport system to maximum without much less accumulation of lactate. Those intervals could be repeated many times before fatigue. Scientific publications of physiological data were published 2 decades later.

If we take, for instance, an interval training of 3 minutes at 100% of the minimal velocity associated with the maximal oxygen consumption ($v\dot{V}O_{2max}$) determined in an incremental test interspersed with 3 minutes at 50% $v\dot{V}O_{2max}$, interval training characteristics as defined by Saltin et al.[4] will have the following characteristics:

(i) the *intensity* is defined as the average power output; for the interval training described above, the average intensity is equal to (100 + 50)/2 = 75% $v\dot{V}O_{2max}$ [about 75% of maximal oxygen uptake ($\dot{V}O_{2max}$)];

(ii) the *time-ratio* for the high and low exercise duration; for the interval training described above, the time ratio 3/3 = 1;

(iii) the *amplitude* is the ratio of the difference between the intensity of the different periods (heavy or recovery run) with the average velocity; for the interval training described above, since the average velocity is 75% $v\dot{V}O_{2max}$, the amplitude is: 100–75/75 = 33%;

(iv) the *duration* and the *distances* run at high and low velocities.

To appreciate both the immediate and the long term effects of interval training programmes, modern, technological progress has provided devices allowing field measurements of the physiological responses of athletes during interval running. The different types of interval training which have been used to improve aerobic and anaerobic capacity are presented in table I.

2. The Pioneers of Interval Training: Physiologists, Trainers and Runners

In 1910, it was possible to measure $\dot{V}O_2$ during exercise but no athletes were tested for training improvement. However, in 1912, the 10 000m Olympic championship runner, Hannes Kolehmainen (Finland), had already used interval training at the specific 10km pace. He had trained using 5 to 10 repetitions of 3 minutes 5 seconds every 1000m (19 km/h). 80 years later the 10km specific interval training is run at 22.7 km/h.

During the 1920s and 1930s, at a time when Hill[5] had invented the concept of $\dot{V}O_{2max}$ and oxygen deficit to explain the shape of the velocity-time relationship, the great Finnish runner, Pavoo Nurmi (who ran the 5000m in 14 minutes 36 seconds at 20.6 km/h), introduced short interval training at an intensity superior to a specific velocity such as 6 × 400m in 60 seconds at 24 km/h inside a slow run of 10 to 20km in the woods.

After the second world war, interval training became a widespread training method used by European runners. Emil Zatopek (Czechoslovakia, triple gold medallist in 1952 in 5000, 10 000m and Marathon events), Gordon Pirie (UK, 3000m in 7 minutes 57 seconds in 1960), Sigfried Hermann (Germany, 800m in 1 minute 48 seconds, and 1500m in 3 minutes 40.9 seconds) trained by Toni Nett, Roger Moens (Belgium), and Vladimir Kutz (USSR, 5000m in 13 minutes 35.0 seconds) all used interval training. The most famous athlete to use interval training was Emil Zatopek who initiated short

Table I. Classification of the different types of interval training according to the specific velocities of a race, the time limit at these velocities and 'physiological velocities': the velocity at maximal oxygen uptake ($\dot{V}O_{2max}$), the critical velocity (i.e. the asymptote of the velocity-time limit relationship), and the velocity at maximal lactate steady state

Intensity (% $v\dot{V}O_{2max}$)	Physiological and competition velocity	Time limit at this velocity (min)	Time spent at $\dot{V}O_{2max}$ (min)	Maximal blood lactate level (mmol/L)	Aerobic metabolism to energy (%)	Anaerobic interval training	Aerobic interval training
115-130	v1000m; v800m	3-2	2-1	15-18	75-65	–6 × 30 sec; R = 30 sec (rest); –60 sec, –45 sec, –30 sec, –45 sec, –60 sec; R = 5 min (rest)	–20 × 10 sec; R = 10 sec (rest)
105-115	vmiles; v1500m	6-4	4-2	13-15	85-80	–6 × 1 min; R = 3 min (rest); –3 × 500m at v1500m; R = 3 min (rest)	–15 × 15 sec; R = 15 sec at 50% $v\dot{V}O_{2max}$
100-105	$v\dot{V}O_{2max}$; v3000m	8-6	5-4	11-13	90-85	–3 × 1000m at v3000m; R = 3 min (rest)	–20 × 15 sec; R = 15 sec at 50% $v\dot{V}O_{2max}$
95-100	v5000m	15-8	10-5	9-11	95-90	–5 × 1000m at v5000m; R = 3 min (rest)	–25 × 15 sec; R = 15 sec at 50% $v\dot{V}O_{2max}$; –6 × 3 min; R = 3 min 50% $v\dot{V}O_{2max}$
90-95	v10 000m and critical velocity	30-15	1-10	7-9	97.0		3 × 3000m at v10 000m; R = 3 min (rest)
85-90	Velocity for record of the hour	60-30	0	5-7	98.0		–2 × 20 min; R = 3 min at 70% $v\dot{V}O_{2max}$
80-85	Maximal lactate steady state	80-60	0	3-5	99.0		-2 × 30 min; R = 3 min at 70% $v\dot{V}O_{2max}$
75-80	Marathon velocity	150-80	0	3-3.5	99.9		2 × 15km; R = 1km at 70% $v\dot{V}O_{2max}$

R = recovery between series (i.e. set of several repetitions); **$v\dot{V}O_{2max}$** = velocity at maximal oxygen uptake; **vxm** = average velocity over *x* metres.

interval training at low amplitudes and running at the critical velocity. His critical velocity, calculated from his personal best in 3 to 10km events according to Ettema,[6] was about equal to 85% $v\dot{V}O_{2max}$, that is, 20 km/h, or 1 minute 12 seconds in 400m or lower at (probably) his maximal blood lactate steady state. Indeed, he repeated up to 100 × 400m repetitions per day, interspersed by 200m of recovery run at a pace close to that of hard work.

Toni Nett (in Reindell et al.[3]) reported the specific interval training programme of Sigfried Hermann for the 1500m (best performance 3 minutes 40 seconds): 4 × (6 × 200m) with a rest of 50 to 60 seconds between runs and of 8 minutes between the series. The first series was run slower (30 seconds, i.e. 24 km/h at 98% of the average velocity over 1500m) and the last series faster [28 seconds, i.e. 105% of the average velocity over 1500m (v1500m) with the last run in 25 seconds, i.e. 118% of v1500m].

If one looks at the variation in pace per 300m, even for the world's records, to choose the intensity and duration of interval training, it seems appropriate to train within the range of the velocity of the race. Therefore, trainers have always started from the requirements of the race, and chosen values appropriate to the best performance of the runner. However, scientists can provide information regarding the physiological responses of the athlete during such interval training and it could be possible to determine the effect of active or passive pause. Unfortunately, interval training studied in the laboratory, even on the treadmill, has been calibrated with reference to $v\dot{V}O_{2max}$ and not to the best performance of the runners. The use of the critical velocity calculated from the slope of the distance-time limit from the best performance over 3000 to 10 000m could be a way to calibrate interval training taking into account the performance instead of a physiological velocity, such as $v\dot{V}O_{2max}$.[7]

By examining the interval training performed during a week by Vladimir Kutz [the average velocity over 5000m (v5000m) = 22 km/h], we can conclude that he practised many series separated by gymnastics. Nowadays, runners train twice a day rather than performing such a long programme. A typical day of training for Vladimir Kutz is presented in table II. Kutz performed interval training in parks or woods. It should be pointed out that in table II the interval training used by Vladimir Kutz was composed of very different distances and velocities, even within the same training session.

In the fifties, Franz Stamfl who trained Roger Bannister, the first sub-4-minute miler, employed interval training in varying forms (aerobic, anaerobic; table I), 5 days per week almost all year round. He preferred his athletes to run fewer miles but he insisted on the quality of work rather than the quantity although, once per week, they did perform Fartlek runs of 60 to 90 minutes duration.[1] However, Fartlek runs were actually previously invented by the Swedish coach Gösta Holmér in the 1930s.

Table II. Summary of a typical day of interval training for Vladimir Kutz (5000m in 13min 35.0sec, v5000m = 22 km/h)

1.	30min of jogging
2.	8 × 100m of acceleration (14sec)
3.	Stretching
4.	20 × 200m in 28-29sec (118% of v5000m) with recovery trot
5.	4 × 400m (68sec, 96% of v5000m) with recovery trot
6.	15min of light running where the runner has to focus on flexible style
Recovery times were not specified	
On Friday the interval training programme was much more consecutive but it was added just before the stretching, 5 × 120-150m at maximal velocity and 20 × 400m (60-68sec)	
It provided:	
1.	30min of jogging
2.	5 × 120-150m at maximal velocity
3.	Stretching
4.	5 × 200m in 28-29sec (118% of v5000m) with recovery trot
5.	20 × 400m (60-80sec in 96-109% of v5000m) with recovery trot
6.	5 × 200m in 28-29sec (118% of v5000m) with recovery trot
7.	15min of light running where the runner has to focus on flexible style
8.	15min of stretching

v5000m = average velocity over 5000m.

2.1 The 1960s

The sixties were the years of the first scientific studies on interval training. In 1960, the pioneer Swedish physiologist Per Oløf Astrand developed long interval training at a velocity between the critical velocity and $v\dot{V}O_{2max}$ (90 to 95% $v\dot{V}O_{2max}$) [table I]. These 3 minutes run at about 90 to 92% of $v\dot{V}O_{2max}$ elicited $\dot{V}O_{2max}$ in the last repetitions, despite the complete rest in between. Astrand et al.[8] considered that this was one of the best forms of interval training to improve $\dot{V}O_{2max}$ since all cardiorespiratory parameters were at their maximum. From the same group of researchers, Christensen et al.[9] proposed very short interval training run at 100% of $v\dot{V}O_{2max}$: 10-second runs interspersed with 10 seconds of complete rest, since $\dot{V}O_2$ reached $\dot{V}O_{2max}$ with a low blood lactate accumulation. In 1960 the first study[9] describing the metabolic response during interval training with particularly short periods from 5 to 30 seconds, was published. This was remarkable considering the absence of automatic methods for measuring $\dot{V}O_2$. They reported that a runner (the individual BS, with a $\dot{V}O_{2max}$ = 5.6 L/min, 67 ml/min/kg), performing very short intermittent runs (15 seconds) of alternating brief heavy intensity repetitions at 100% of $v\dot{V}O_{2max}$ with complete rest (15 seconds), sustained this exercise for 30 minutes with a low level of blood lactate (2.3 mmol/L). Moreover, this runner reached $\dot{V}O_{2max}$ at the end of the exercise. Using shorter pauses (10 seconds) BS reached 95% of $\dot{V}O_{2max}$ by the 18th minute and the end blood lactate level stayed rather low, that is, 5.6 mmol/L. However, because of passive recovery this value fluctuated between 89 and 95% of $\dot{V}O_{2max}$. With shorter work and pauses (5 seconds, 5 seconds), this individual reached only

81% of $\dot{V}O_{2max}$ but this value was more constant because of the very brief pause. The end blood lactate level was just above 2 mmol/L (2.5 mmol/L), similar to that seen with very short intermittent runs and pauses (15 seconds, 15 seconds).

In the 1960s, the first studies by the Astrand and Christensen group examining the immediate and long term effects on metabolism were published. In the first study,[10] they compared the same work performed at the same power output (360W and almost 98% of power output, i.e. $p\dot{V}O_{2max}$) but with different work durations (30 seconds, 1, 2 and 3 minutes). The continuous time limit of this heavy exercise was equal to 9 minutes. It was found that when the cycling exercise was split into short periods of work and rest it was transformed into a submaximal load on both circulation and respiration (63% $\dot{V}O_{2max}$, blood lactate level 2 mmol/L) and, hence, was well tolerated during 1 hour. With longer periods (2 or 3 minutes duration) the work output became close to the upper limit of performance and could be fulfilled only with the utmost strain (blood lactate of 16.6 mmol/L, and $\dot{V}O_{2max}$ at 100%). From a practical point of view the authors stressed that by choosing longer periods, for example 2 or 3 minutes, one could obtain a higher training effect on cardiorespiratory function. Moreover, to explain the low lactic acid values during the short periods of work and rest it was proposed that the myoglobin functions as an oxygen store during short spells of heavy muscular work.[8]

In another paper published in the same volume,[11] the same group hypothesised that myoglobin would represent an oxygen store which is used during the initial phase of work before respiration and circulation are able to reach the values which correspond to the actual oxygen demand. This oxygen store was calculated to be equal to 0.43L, which represents about 10% of the maximal accumulated oxygen deficit obtained in an all-out exercise of 2 minutes.[12]

These investigators also described the oxygen kinetics in the all-out exercise at $p\dot{V}O_{2max}$ (time limit: 9 minutes). They emphasised that the time course of oxygen increase was dependent on the work output and the fitness of the individual and was exceptionally resistant to changes in the mental state of the trained individual. They pointed out the fact that in 4 minutes (for this individual and at this work rate) the athlete reached $\dot{V}O_{2max}$. This fact is of importance when the purpose is to choose the duration of interval training. Indeed, about 50% of the time at this work rate is required to reach $\dot{V}O_{2max}$. If the goal is to elicit $\dot{V}O_{2max}$ at the first repetition, the duration must be equal to at least 50% of the time limit.[13] Astrand and Saltin, in 1961,[14] demonstrated that because of the acceleration in oxygen kinetics with high work rate, $\dot{V}O_{2max}$ was reached and maintained (about half of the time limit) for exercises lasting between 2 and 8 minutes. Actually, oxygen peak could, after warming up, be attained within 1 minute. More than 10 years later, the same team,[15] did biopsies after each of the 5 repetitions of 1 minute of exercise at about 120% of $p\dot{V}O_{2max}$ followed by 5 minutes of rest. Creatine phosphate (CP) was progressively depleted after each repetition and muscle lactate level reached its highest value (23 mmol/L/kg wet muscle), at the first work period. Blood lactate levels took more time to increase, but reached 20 mmol/L by the third repetition. Hermansen[16] had previously reported very high levels of blood lactate (30 mmol/L) using the same kind of interval training.

At the end of the sixties, the American group of Fox et al.[17] focused on interval training in a military context.[17,18] They compared metabolic energy sources during continuous and interval running at the same rate. Moreover, they compared the physiological response for a recovery run (60% of $v\dot{V}O_{2max}$) or passive complete rest. They emphasised that coaches had succeeded in improving the performance of highly trained athletes using the interval training method. These investigators explained this by the fact that there is a slower accumulation of lactic acid, and therefore a delay in the onset of fatigue. This results from the replenishment and subsequent reutilisation of part of the phosphagen reserves which enable the athlete to accomplish large quantities of work (distance) at very high intensities. However, these investigators advised coaches to alternate the work intervals with rest, rather than running, to be able to restore phosphocreatine reserves. They did not control the amount of time spent at $\dot{V}O_{2max}$, but just the work performed at high intensity, which supports the training concept of Tim Noakes,[19] but is in contrast to that of Jack Daniels.[20]

During the same period, the New Zealand trainer Arthur Lydiard (who trained Peter Snell, double gold medallist in 1960) also developed a very short interval training method run at 100% of $v\dot{V}O_{2max}$. The duration of this short interval training, run at 100% of $v\dot{V}O_{2max}$, was 10- to 15-second runs with pauses of the same duration run at 30 to 40% of $\dot{V}O_{2max}$. We shall see in section 3 that this procedure of short interval training at 100% $v\dot{V}O_{2max}$ with active pauses allows the runner to stay a very long time at $\dot{V}O_{2max}$. Indeed, this has recently been demonstrated on the track using a portable breath by breath gas exchange analyser (K4b2, Cosmed, Italy). In addition to this short interval training, Lydiard's athletes (even the middle-distance runners) regularly performed training runs of 2 hours duration (100 miles per week) as the Kenyans do today.

In the sixties, Wasserman and McIlroy[21] invented the concept of anaerobic threshold (1964) as a pathological diagnostic tool. However, this concept has not yet been used to delineate training velocity zones and training in this velocity range was done as a form of Fartlek.

In 1967, the Swedish physiologists Bengt Saltin and Per Oløf Astrand[22] published data on $\dot{V}O_{2max}$ for athletes including the world record holder for 3000m (7 minutes 39 seconds), Kip Keino. They reported the highest value recorded for a runner (82 ml/min/kg), not much higher than that reported in 1937 by Robinson et al.[23] for the 2 mile world record holder, Donald Lash who had a $\dot{V}O_{2max}$ of 81 ml/min/kg. However, considering the $v\dot{V}O_{2max}$ value reported (21.6 km/h) on the level treadmill, these data were probably not overestimated. In 1955, Astrand published higher values[24] found in cross–country skiers. However, despite these prestigious papers, no $\dot{V}O_{2max}$ values were routinely measured for training advice purposes.

2.2 The 1970s and 1980s

During the seventies $\dot{V}O_{2max}$ began to be systematically measured in athletes, and in the eighties the lactate threshold was measured. East German physiologists, such as Alois Mader, determined a blood lactate threshold at 4 mmol/L using stages of constant velocity, 5 minutes long (for review see Billat[25]).

The eighties were years of exceptional runners such as Sebastian Coe (800 to 1500m). Coe was trained by his father Peter who was very inspired by scientific methods. Sebastian Coe performed aerobic and anaerobic interval training as well as circuit training for strength and power improvement. North African runners, such as Said Aouita the great middle-distance runner (who held the world records for the 1500 to 5000m) used interval training sessions with different velocities. In the same interval training session, he ran at velocities from the maximal lactate steady-state velocity to v5000 (94% of $v\dot{V}O_{2max}$) and then to v1500m in the same interval training session (distance varying from 3000 to 200m).

Trainers used specific velocities from 800 to 5000m to calibrate their interval training without taking into account the physiological markers. Daniels et al.[26] defined the parameter $v\dot{V}O_{2max}$ as the velocity associated with $\dot{V}O_{2max}$ determined by an incremental work test on a treadmill. Furthermore, this $v\dot{V}O_{2max}$ was found to be close to the average velocity sustained over 3000m.[26,27]

The concept of velocity associated with the $\dot{V}O_{2max}$ appeared at the beginning of the eighties with Daniels et al.,[28] di Prampero[29] and the maximal aerobic speed of the Montreal track test of Léger and Boucher[30] (for review, see Billat and Koralsztein[31]). This last test allowed one to have an estimate of $\dot{V}O_{2max}$ (with an average energy cost of running) and provided the minimal velocity eliciting $\dot{V}O_{2max}$ in an incremental test.

However, Karlsson et al.[32] had already shown in 1967, that the speed exhausting runners in 4 min-

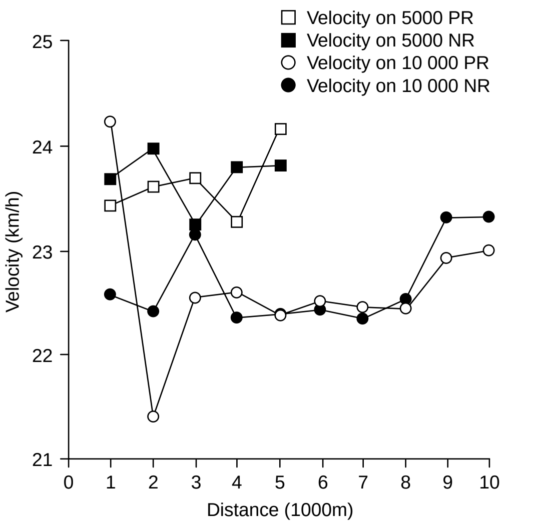

Fig. 1. Variation in velocity during 5000 and 10 000m of the previous record (PR) and of the new world record (NR) for the 5000 and 10 000m events.

utes could be reduced to 80% (–3 km/h), without decreasing their oxygen consumption. It is now well known that the minimal velocity which elicits $\dot{V}O_{2max}$ in a steady-state velocity condition is below $v\dot{V}O_{2max}$ (found in incremental 3-minute stages), and is set just above the critical velocity, in the mid range between the velocity at the maximal lactate steady state (v_{MLSS}) and $v\dot{V}O_{2max}$ (the so-called $v\Delta50$ velocity).[33]

Indeed, $v\dot{V}O_{2max}$ is easy to measure with an incremental test and can be used as a reference for interval training calibration. Moreover, out of competition season it seems better to refer to the velocities associated with particular physiological responses in the range from maximal lactate steady state to the absolute maximal velocity. The range of velocities used in the race must nevertheless be taken into consideration, since even world records are not run at a constant pace. Figure 1 shows the velocity change in the world record race over 10 000 and 5000m, and one can appreciate that the competition is also a type of interval running. If we consider the training of the best middle- and long-distance runners of the 20th century (table III), it can be seen that they have available a very wide range of velocity and interval training from v_{MLSS} to maximal speed.

Another key factor, as we shall see in this review, is strength and power development which becomes more and more important in improving performance over long distances (by decreasing the cost of activity). This was emphasised by trainers such as Percy Cerutty who trained Australian distance runners (Herb Elliott and John Landy) who dominated the international competitions in the late 1950s and early 1960s. He asked these runners to perform interval runs up sand-hills as well as undertake extensive weight training sessions. He recommended that all distance runners spend at least a third of their training time in nonrunning activities, in particular weight training, which can be organised as an interval training (called ‘circuit training’). Cerutty emphasised that there were 2 important aspects during training: (i) to run at competitive speed [not full distance]; and (ii) to train at high velocity continuously for the full distance. However, almost everything was included in his programme.

This requirement of using weight training was confirmed recently by Paavolainen et al.[34] who reported that the velocity over 5km was positively correlated with the maximal velocity, the contact time and the stride rates over 20m (running start). Both the velocities over 5 and 10km were correlated with the mean contact time of the constant velocity laps during 5 and 10km. The ability of fast force production during maximal and submaximal running was related to both the 5 and 10km performance.[34] The same group of researchers also showed that explosive strength training (various sprint, jumping exercises, leg press and knee extensor-flexor exercises) replacing 32% of the training volume induced a significant decrease in the 5km time.[35] This increase in performance was related to the improved running economy and the velocity reached in an anaerobic treadmill running test.[36]

Another new interval training technique could be to use different sports (cycling and running for instance) simultaneously in the same interval training session. This has been used by triathletes to

Table III. Summary of some of the greatest champion's training referenced with physiological marker velocities[a]

Year; *name*; best performance	$v\dot{V}O_{2max}$ (km/h); $\dot{V}O_{2max}$ (ml/min/kg)	$\leq v_{MLSS}$ [b]	Critical velocity[c]	90-100% $v\dot{V}O_{2max}$ [d]	$>v\dot{V}O_{2max}$ [d]
1920; *Paavo Nurmi*; 14 min 28 sec over 5000m (20.7 km/h); 30 min 6 sec over 10 000m (19.9 km/h); 1 training/day	22.0; 75	15-20 km/day		20 × 100m, R = 200m walked	4 × 400m at maximal velocity over 400m, R = 15 min rest
1950; *Emil Zatopek*; 13 min 57.02 sec over 5000m (21.5 km/h); 28 min 54.02 sec over 10 000m (20.8 km/h); 2 trainings/day	23.5; 76.2	20 km/day	20 × 200m + 40 × 2 + 400m + 20 × 200m = 200m trot; or 50 × 200m morning and afternoon	40 × 200m, r = 200m jogged	6 × 400m at 90% of maximal velocity over 400m, R = 10 min rest
1968; *Kip Keino*; 7min 39.05 sec over 3000m (23.5 km/h); 13 min 36.05 sec over 5000m (22.1 km/h); 2-3 trainings/day	23.5; 80.0	5 × 45 min or 6 × 60 min		10 × 400m, r = 2 min jogged; or 6 × 800m, R = 3-5 min jogged	10 × 200m + 10 × 100m + 4 × 80m at 90% of the maximal velocities over the distances, r = 300m walked
1972-1976; *Lasse Viren*; 13 min 16 sec over 5000m (22.6 km/h); 27 min 38 sec over 10 000m (21.7 km/h); 2-3 trainings/day	24.0; 83.0	80km per week at 100 bpm	130km Fartlek (over 12-15km)	10 × 200m, r = 2 min; or 6 × 800m, r = 3-5 min jogged	8 × 600m, r = 600m walked
1984; *Grete Waitz*; 15 min 8 sec over 5000m (19.8 km/h); 30 min 59.08 sec over 10 000m (19.4 km/h); 2h 25 min 28 sec in marathon (17.4 km/h); 2 trainings/day	21.0; 73.0	45 min-2h every day	20 min at CV in 60 min of running (tempo training)	6 × 1000m, r = 1 min; or 5 × 1600m, r = 2 min jogged; or 5 × 2000m, r = 3 min jogged	2 × (10 × 300m), r = 100m walked, R = 5 min walked
1986; *Ingrid Kristiansen*; 14 min 37.03 sec over 5000m (20.5 km/h); 30 min 13.07 sec over 10 000m (19.9 km/h); 2h 21 min 6 sec in marathon (17.9 km/h); 2 trainings/day	21.7; 76.0	45-150 min every day	2 × 15 min at CV in 90 min run (tempo training)	5 × 1000m, r = 2 min	2 series of 5 × 100m, r = 200m walked, R = 400m walked

a $v\dot{V}O_{2max}$ and $\dot{V}O_{2max}$ were estimated from the runner's personal best over 3000m (97% of $v\dot{V}O_{2max}$). CV was computed from their personal best over 3000 to 10 000m.[6]

b Run over a distance (km/day or km/week) or for a duration (min) 80% $v\dot{V}O_{2max}$.

c Run over a distance (m or km) or for a duration (min) 85% $v\dot{V}O_{2max}$.

d Run over a distance (m or km) or for a duration (min).

bpm = beats per minute; **CV** = critical velocity; **R** = recovery between series (i.e. set of several repetitions); **r** = recovery between repetitions; $\mathbf{v_{MLSS}}$ = velocity at the maximal lactate steady state; $\dot{V}\mathbf{O_{2max}}$ = maximal oxygen uptake; $\mathbf{v\dot{V}O_{2max}}$ = velocity at maximal oxygen uptake.

elicit longer $\dot{V}O_{2max}$ in the same training session and to become accustomed to working successively with different muscle masses. However, cross-training has been reported to be less effective in improving $\dot{V}O_{2max}$ especially in highly trained individuals.[37,38] The ideal cross-training could be a mixture of aerobic and anaerobic interval training for both short-long sprint (400m run) and middle-distance runners (800 to 5000m).[39]

Multiple regression analyses have indicated that the maximal accumulated oxygen deficit was the best metabolic predictor for 100, 200 and 400m performance, and that the peak oxygen uptake ($\dot{V}O_{2peak}$) was the best predictor for 800, 1500 and 5000m performance.[40] However, Spencer et al.[41] clearly demonstrated that even over 400m the role played by the aerobic energy system is more important. Indeed, $\dot{V}O_{2max}$ was elicited in the last 20 seconds of a 400m run in 52 seconds (run at 170% of $v\dot{V}O_{2max}$). The energy produced by oxidative phosphorylation was 46% of the total energy versus 69 and 83% for a 800m and 1500m run in 1 minute 58 seconds and

4 minutes 2 seconds, respectively (regional performance). The maximal accumulated deficit was the same over all these distances. This confirmed the hypothesis of Hill[42] explaining the decrease of velocity with time; the fact that the oxygen deficit was divided by a longer time decreased the power output. As noted by Houmard et al.,[43] anaerobic systems influence middle-distance performance in runners of similar abilities.

Thus, all types of interval training should be used, especially in middle-distance runners up to 10km and perhaps, in the future, for marathon runners. The last lap of a 10 000m race is currently run in less than 1 minute (>24 km/h), well above the runner's $v\dot{V}O_{2max}$.

3. Aerobic Interval Training

3.1 Immediate Responses to Aerobic Interval Training

Aerobic training is defined as an interval training which elicits aerobic metabolism at a higher ratio than anaerobic metabolism. This can be estimated from the ratio between the accumulated oxygen deficit and the oxygen consumed in interval training.

3.1.1 Short Aerobic Interval Training

Short aerobic interval training has been shown to prevent glycogen depletion by using lipids compared with continuous exercise performed at the same velocity. A high intensity exercise (100 to 102% of $p\dot{V}O_{2max}$) performed continuously (time limit = 4 to 6 minutes) or intermittently (112% of $p\dot{V}O_{2max}$) for 60 minutes (15 seconds of work and 15 seconds of rest) did not deplete muscle fibres in the same way.[44] The blood lactate level was equal to 2 mmol/L in the intermittent exercise versus 10 mmol/L in the continuous one. Indeed, after 60 minutes of intense interval training, a significant and similar depletion occurred in both type I and type II (A + B) fibres. With continuous intense exercise to exhaustion, glycogen depletion was more marked in type II (A + B) than type I fibres. In fact, intermittent exercise depletes muscle fibres in an intermediate way between continuous submaximal (50% of $p\dot{V}O_{2max}$) and all-out exercise (6 minutes) at 100% of $p\dot{V}O_{2max}$. With active pause, it may be that, since the average power output is higher, intermittent exercise is closer to continuous maximal exercise at 100% of $p\dot{V}O_{2max}$ concerning muscle fibre type recruitment and enhancement of the glycogenolysis since CP has less time to be reconstituted. Moreover, during intermittent exercise a lower glycogen depletion may be explained by a relative increase in the contribution of lipids to oxidative metabolism.[45] These could also increase levels of adenosine triphosphate (ATP), CP and citrate at the end of each rest period, which would suppress glycolysis in the early phase of the subsequent work period.

As a consequence of the brief work intervals, oxygen stored in myoglobin (400ml) can supply half of the oxygen requirement. As underlined by Christensen et al.,[9] there may be an increased availability of oxygen because of the reloading of myoglobin stores in the resting periods and subsequently a greater aerobic energy output which would give a higher ATP production per glucose unit compared with lactate formation. In fact, for the purpose of maximally taxing the oxygen-transport system, Astrand and Rodahl[46] recommended intermittent 10-second runs and 5-second pauses to reach $\dot{V}O_{2max}$. A well trained athlete ($\dot{V}O_{2max}$ = 5.3 L/min) is able to sustain this configuration of exercise for 30 minutes with an effective run time at $v\dot{V}O_{2max}$ of 20 minutes (since the work : rest ratio was 1/2). The oxygen deficit (the difference between the amount of oxygen needed and the amount of oxygen actually consumed), was thought to be accounted for by the utilisation of other energy stores such as high energy phosphates (e.g. phosphocreatine) and the oxygen bound to myoglobin.

Olbrecht et al.[47] have demonstrated that in swimming, the velocities during brief intervals of 10-second swims with rest periods of 10 seconds were higher than those corresponding to the same lactic acid levels during continuous swimming, +11.2, 4.2, 2.9 and 2.0% of the velocity at the 4 mmol/L level on 50, 100, 200 and 400m, respectively. The velocity on the basis of the 4 mmol/L level was obtained from the 2-speed test (2×400m).[47] This short rest of 10 seconds allowed the swimmer to regenerate the myoglobin oxygen reserve but probably not the CP reserve. With a longer rest (30 seconds) the increase in the velocity compared with continuous work was 1.5-fold greater than those obtained with a rest of 10 seconds.

In rowing, short interval training with 15 seconds at the competition velocity (since the competition lasts 6 minutes, it is probable that the rowers elicit 100% of $\dot{V}O_{2max}$) and 15 seconds of rest has also been tested.[48] This was performed as 5 sets of 5 repetitions. Each set was separated by 30 seconds of rest. During the intermittent rowing, no significant differences were detected in any of the variables measured between sets. Heart rate, $\dot{V}O_{2peak}$ and blood lactate averaged 89, 78 and 32%, respectively, of values measured during the continuous incremental exercise test. Therefore, with rowing, the investigated 15/15 intermittent exercise model demands relatively high aerobic loading and low glycolytic activity. Gullstrand[48] concluded that this type of interval training may be considered as an alternative model for training which would allow the rowers to work for prolonged periods of time at values slightly above competition intensity.

The short interval training currently being used by runners and studied by researchers is the 30–30-second work : rest pattern. Thirty years ago, Edwards et al.[49] had already measured, breath by breath, oxygen kinetics in 30-second interval training during active pause performed at 50% of a work rate associated with a time limit of 6 minutes (close to the power output at $\dot{V}O_{2max}$: $p\dot{V}O_{2max}$). This was carried out on a cycle-ergometer. The work : pause ratio was 1 and the interval duration was 30 seconds. They emphasised that $\dot{V}O_2$ (ventilation and heart rate) remained high throughout the 20-second recovery intervals and did not fall appreciably until 30 seconds after the end of the last work period. With passive rest in a 30–30-second interval training performed at 120% $v\dot{V}O_{2max}$, $\dot{V}O_2$ reached only 70% of $\dot{V}O_{2max}$ during the work periods (and 14 mmol/L of blood lactate).[50]

Gorostiaga et al.[51] showed that interval training with repetitions of 30 seconds work at 100% $v\dot{V}O_{2max}$, separated by 30 seconds of rest, produced a greater increase in $\dot{V}O_{2max}$ than continuous training at 70% $v\dot{V}O_{2max}$. In this last study, both continuous or intermittent training only elicited a $\dot{V}O_2$ which was 70% of $\dot{V}O_{2max}$. All of these studies were aimed at improving $\dot{V}O_{2max}$ and were based on the assumption that the more specific the stimulus, (i.e. taxing the cardiovascular and aerobic enzymatic system to their maximum) the greater the improvement. However, again, none of these studies measured the time the athlete spent at $\dot{V}O_{2max}$.

It is interesting to note that none of the previous studies checked if their participants had reached $\dot{V}O_{2max}$ during the interval training session. However, Astrand et al.[8] reported that interval training of 2 minutes run at $v\dot{V}O_{2max}$ alternated with inactive rest of the same duration elicited a $\dot{V}O_2$ equal to 95% of $\dot{V}O_{2max}$ accompanied by a very low blood lactate level (2.2 mmol/L). The same study also reported that interval training using shorter repetitions (15 seconds at $v\dot{V}O_{2max}$ alternated with 15 seconds of complete rest) did not bring the $\dot{V}O_2$ to maximum levels.

Billat et al.[52] reported that in a 30–30-second, short interval training, the 30 seconds of recovery is active (50% $v\dot{V}O_{2max}$), and runners stayed at $\dot{V}O_{2max}$ even during the recovery period from the fifth to the last (18th) repetition of a 30-second run at $v\dot{V}O_{2max}$, and a 30-second run at 50% of $v\dot{V}O_{2max}$. This short interval training with active pauses allows individuals to sustain $\dot{V}O_{2max}$ for 10 minutes (83% of total time run at $v\dot{V}O_{2max}$). The average blood lactate end value was 7.4 ± 1.8 mmol/L. Runners reached $\dot{V}O_{2max}$ during the intermittent exercise, the associated blood lactate was at a steady-state level and from the third to the sixth minute was below 4 mmol/L. Hence, for at least 1 minute, these 5 runners were at $\dot{V}O_{2max}$ with only 4 mmol/L of blood lactate. This is interesting since in previous studies which have examined blood lactate accumulation during intermittent exercise, it has been reported that only a high value of blood lactate accompanies a $\dot{V}O_2$ at its maximum value.[8] This is because of the fact that these studies have used long 2- to 3-minute intervals to elicit $\dot{V}O_{2max}$ with complete rest between repetitions. Therefore, when using the 30-second rest/exercise intervals with inactive pause they did not reach $\dot{V}O_{2max}$.

Interval training performed at velocities close to the velocity associated with $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$) may maximise the improvement in $\dot{V}O_{2max}$, as well as result in significant improvements in mitochondrial density.[53] In fact, in addition to these aerobic (O_2 transport) training benefits, interval training stimulates the rate of lactate removal which depends directly on its level (i.e. the greater the level, the greater the removal).[53] Therefore, interval training that increases blood lactate levels will also stimulate lactate removal. For this reason Brooks et al.[53] recommended activity during the rest interval to stimulate this lactate removal and hence avoid blood lactate accumulation. Indeed, in 1937 Newman et al.[54] had already noticed that the removal of lactate, accumulated after exhausting exercise, was enhanced if the individual continued to exercise during recovery, but at lower intensity, which normally did not accumulate lactate. This information, confirmed in 1975 by Belcastro and Bonen,[55] was applied in training programmes for elite athletes in the 1950s. Despite high lactate production at the high velocities used in interval training (i.e. above the lactate threshold) walking or jogging in the rest phase of intermittent exercise would tend to stimulate oxidative recovery.[56] Therefore, we suggest that active, rather than passive, pauses between the intervals of hard work will not only elicit and maintain $\dot{V}O_{2max}$, but will also stimulate lactate removal whilst remaining close to the maximal blood lactate steady state.

The blood lactate values obtained at the end of the intermittent tests (6.8 ± 2.2 mmol/L) are of a similar magnitude to those reported by Gimenez et al.[57] These authors used a 45-minute exhaustive 'square wave' endurance exercise test composed of 9 repetitions with 1 minute at $v\dot{V}O_{2max}$ and 4 minutes at 50% $v\dot{V}O_{2max}$. This blood lactate level is also in accordance with that reported by Billat et al.[13] during running with interval training periods at $v\dot{V}O_{2max}$ (intervals set at 50% of the individual's time to exhaustion at $v\dot{V}O_{2max}$) separated by active pauses of the same duration run at 50% $v\dot{V}O_{2max}$. Saltin et al.[4] found similar blood lactate values at the end of 30 minutes of intermittent cycling with intervals of 30 seconds of supramaximal work (400W, %$\dot{V}O_{2max}$ not specified) and 60 seconds of rest. By using the same ratio (1 : 2) between rest and exercise but by increasing the time by 2 (i.e. 60 seconds work and 120 seconds rest), their participants tripled their end blood lactate values (18 mmol/L).

However, if we consider, endurance (time to exhaustion) at $\dot{V}O_{2max}$, it would be interesting to compare the influence of training using protocols which elicit $\dot{V}O_{2max}$ but which are run at different velocities ($v\Delta50$ versus $v\dot{V}O_{2max}$ for instance). In accordance with Noakes,[19] the benefits of training also depend on the distance covered at a high velocity determining the muscular adaptation maximising the number of powerful muscle contractions. For this purpose, the intermittent exercise training at $v\dot{V}O_{2max}$, not only allows the cardiovascular function to be stimulated at its maximum (at $\dot{V}O_{2max}$) for a longer time, but allows the run to be made at a higher velocity (+1.6 km/h). Therefore, both from the cardiovascular and muscular adaptation point of view, intermittent exercise at $v\dot{V}O_{2max}$ is likely to produce increased performance for middle-distance runners.

Before speculating on the cause of $\dot{V}O_{2max}$ improvement from a given training design, it is essential to examine the effect of this stimulus on cardiovascular and metabolic responses. In the absence of this information, we can only hypothesise that the benefit of these training procedures on aerobic capacity (and especially on $\dot{V}O_{2max}$) is dependent not only on the time spent at $\dot{V}O_{2max}$ but also on the distance run at a high velocity. With this in mind we are then able to discriminate between the benefits gained from either interval or constant load tests.

3.1.2 Long Aerobic Interval Training

In addition to the above studies, it has been stated for a long time now that a typical endurance training programme consisting of repeated 1- to 8-minute runs at 90 to 100% v$\dot{V}O_{2max}$ is the most effective programme for improving $\dot{V}O_{2max}$ and performance for middle-distance runners.[58] During interval training lasting 7 × 2 minutes at p$\dot{V}O_{2max}$ (with recovery periods long enough to allow heart rate to return to 130 bpm), $\dot{V}O_2$ reached 70% of $\dot{V}O_{2max}$ in the first minute and 100% of $\dot{V}O_{2max}$ in the second minute. Therefore, with this active recovery procedure (heart rate being at 130 bpm at the end of the recovery), it took only 1 minute to reach $\dot{V}O_{2max}$ when running at 100% v$\dot{V}O_{2max}$. The total time spent at $\dot{V}O_{2max}$ was 7 minutes in all 7 work intervals. However, the time spent at $\dot{V}O_{2max}$ in this 2-minute interval training at v$\dot{V}O_{2max}$ was no longer than that during an all-out run at a submaximal velocity inducing a slow phase of oxygen kinetics (90% v$\dot{V}O_{2max}$).[59]

Therefore, 30 seconds appears to be the longest interval duration allowing work at p$\dot{V}O_{2max}$ to elicit $\dot{V}O_{2max}$ even in the recovery period. One or 2 minutes at p$\dot{V}O_{2max}$ induces high blood lactate levels because of the depletion of CP and the use of the oxygen myoglobin-bound oxygen reserve. A recovery period of the same duration as the work period (1 to 2 minutes) allows the rephosphorylation of CP but decreases oxygen consumption. Moreover, passive or a low work rate (40% of $\dot{V}O_{2max}$) in the recovery phase, allows the CP store to be replaced and avoids a high blood lactate level. However, using a higher work rate during recovery, Fox et al.[60] demonstrated that when CP renewal is partially blocked by performing aerobic work (60% v$\dot{V}O_{2max}$) rather than resting during the relief intervals, a greater proportion of the energy needed during the work intervals was supplied by the anaerobic lactic metabolism.

Hence, long interval training is difficult to manage if one wants to avoid acidosis. To 'calibrate' the intensity of interval training, coaches often refer to the running velocity associated with the achievement of $\dot{V}O_{2max}$ during an incremental treadmill test (v$\dot{V}O_{2max}$) and to the running velocity at the onset of blood lactate accumulation (v_{OBLA}). These have both been reported to be relevant indicators of performance for middle- and long-distance running events.[7,25,27,31,61,62] Optimal improvement in cardiorespiratory fitness is thought to be induced by training at an intensity corresponding to 90 to 100% of $\dot{V}O_{2max}$.[63]

The duration of intermittent effort varies considerably depending upon the author. In training for track and field events, intervals between 10 seconds to 3 minutes, generally spaced by inactive rest, have been investigated but have not been referenced to individual possibilities to sustain high intensity exercise (i.e. time to exhaustion at v$\dot{V}O_{2max}$).[31] Training with intermittent runs at 60 and 100% of v$\dot{V}O_{2max}$ (with a duration equal to half of the individual time to exhaustion at v$\dot{V}O_{2max}$) allowed long-distance runners to double the distance covered at v$\dot{V}O_{2max}$ compared with continuous training runs at v$\dot{V}O_{2max}$.[13] More recently, Billat et al.[64] and Smith et al.[65] have reported that only 1 session per week (for 4 weeks) of this kind of individualised interval training (50 to 75% of the time to exhaustion v$\dot{V}O_{2max}$) significantly increased v$\dot{V}O_{2max}$ in a group of middle- and long-distance runners.

To calibrate long interval training, time to exhaustion at the velocity associated with $\dot{V}O_{2max}$ could be a new parameter which could be used to determine a rational basis for interval training in elite middle- and long- distance runners.[13] Therefore, the use of time to exhaustion (time limit = t_{lim}) at v$\dot{V}O_{2max}$ could allow elite long-distance runners to run longer distances at v$\dot{V}O_{2max}$ during interval training. Since time to exhaustion at v$\dot{V}O_{2max}$ has been previously reported to be very different among runners with the same v$\dot{V}O_{2max}$, we hypothesised that this could be a rational basis for determining the length of the work intervals. We have compared the distances run with the physiological responses at the end of 2 interval training sessions that were performed on a treadmill and run at v$\dot{V}O_{2max}$. Two exhaustive intermittent tests were performed, one using a standard 2-minute duration for the alternating exercise and recovery periods, the other using durations that were individually determined based on time spent at v$\dot{V}O_{2max}$. The study involved 16 male 'good level' runners ($\dot{V}O_{2max}$ and v$\dot{V}O_{2max}$ were 69.1 ± 4.3 ml/min/kg and 21.4 ± 1 km/h, respectively).[13] When the intermittent exercise training stimulus was standardised by alternating duration equal to 50% of the time spent at $v\dot{V}O_{2max}$ (with equal periods of recovery run at 60% $v\dot{V}O_{2max}$), the total time at $v\dot{V}O_{2max}$ was 2.5 times the continuous time limit whatever the value of time to exhaustion at $v\dot{V}O_{2max}$. This means that all of the runners were able to run 5 repetitions at 50% of their continuous time to exhaustion at $\dot{V}O_{2max}$.[13]

We are going to consider now, the very long interval training at velocities between the v_{MLSS} and $v\dot{V}O_{2max}$. Continuous running above the running velocity at which the critical velocity is attained[66] could be more efficient to elicit $\dot{V}O_{2max}$ of longer duration than interval training at $v\dot{V}O_{2max}$.[67] Indeed, previous studies reported that during 'severe exercise' an additional slow phase of $\dot{V}O_{2max}$ (the $\dot{V}O_2$ slow component) is superimposed upon the underlying $\dot{V}O_2$ kinetics and $\dot{V}O_2$ continues to increase until the end of the test or until exhaustion, and will possibly drive $\dot{V}O_2$ to the $\dot{V}O_{2max}$.[68,69]

Therefore, by using this $\dot{V}O_2$ slow component phenomenon, it might be possible to elicit $\dot{V}O_{2max}$ for a longer time, provided the individuals run for a sufficiently long period at this supra-critical velocity.[33] In this last study, the work rate chosen was in the mid range of the work rates associated with maximal lactate steady state and $v\dot{V}O_{2max}$ (called '$v\Delta50$'). In fact, 5 runners out of 8 reached $\dot{V}O_{2max}$ during this severe constant load run. Therefore, continuous running at $v\Delta50$ can be used to elicit $\dot{V}O_{2max}$ in a group of middle level runners (15 minutes 30 seconds for 5000m) having a high fractional $\dot{V}O_{2max}$ at the lactate threshold but not a very high $\dot{V}O_{2max}$. Indeed, most of this group of runners (6 of 8) developed a $\dot{V}O_2$ slow component during track running at $v\Delta50$. However, this was not the case in a study of high level runners having a similar endurance capacity (i.e. v_{MLSS} at 84% of $v\dot{V}O_{2max}$) but with a $\dot{V}O_{2max}$ which was 23% greater (75 *vs* 61 ml/min/kg).[70]

Moreover, Billat et al.[70] reported that in a supra-critical velocity run (90% $v\dot{V}O_{2max}$),[66] these 14 highly trained long-distance runners reached a $\dot{V}O_2$ steady state, but did not reach their $\dot{V}O_{2max}$ levels over time ($\dot{V}O_2$ reached = 69.5 ± 5.0 *vs* $\dot{V}O_{2max}$ of 74.9 ± 3.0 ml/kg/min). In other words, highly trained long-distance runners did not exhibit the $\dot{V}O_2$ slow component when performing exhaustive, supra-critical velocity runs at 90% $v\dot{V}O_{2max}$, significantly above their critical and lactate threshold velocities (at 82 and 86% of $v\dot{V}O_{2max}$, respectively). Instead, these runners maintained a steady-state $\dot{V}O_2$ below $\dot{V}O_{2max}$, such that the time to exhaustion at 90% of $v\dot{V}O_{2max}$ for these runners was positively correlated with the critical velocity expressed as a percentage of $v\dot{V}O_{2max}$. Critical velocity is known to correspond to an exercise intensity that lies between the work rate associated with the lactate threshold and $\dot{V}O_{2max}$.[33] It has been suggested that this intensity is comparable to that achieved in a competitive 10km race.[68,71] In addition, Gaesser and Poole[67] have proposed that during prolonged exercise at intensities above the critical velocity, $\dot{V}O_2$ would continue to rise until $\dot{V}O_{2max}$ is reached.

However, the results from the study of Billat et al.[70] reported that a $\dot{V}O_2$ slow component was not expressed by high level long-distance runners during exhaustive supra-critical velocity runs at 90% of $v\dot{V}O_{2max}$. Indeed, although these runners were assigned to run at a work rate which was 5% above their critical velocity (90% of $v\dot{V}O_{2max}$), they reached a $\dot{V}O_2$ steady state at an average of 93% of $\dot{V}O_{2max}$ for 17 minutes and did not demonstrate a progressive increase in $\dot{V}O_2$ over time. At the end of this all-out run they had a blood lactate level of 6.5 mmol/L, a value of the same magnitude as those obtained in the present study.

Indeed, the $\dot{V}O_2$ slow component appears in individuals having a smaller $\dot{V}O_{2max}$ rather than elite athletes. Therefore, it is possible that continuous severe exercise (i.e. $v\Delta50$) cannot be used to stimulate $\dot{V}O_{2max}$ for highly trained runners who already have a high $\dot{V}O_{2max}$ (>70 ml/min/kg).

Most previous investigations have described a slow phase of $\dot{V}O_2$ during intense cycling exercise performed by untrained individuals.[68,72-74] For untrained individuals, endurance training has been shown to reduce the magnitude of the slow component,[75] and it can be suggested that for them, long interval training at $v\Delta 50$ can be used to stimulate $\dot{V}O_{2max}$. This kind of continuous supra-critical velocity is known as tempo training and is often used for training long-distance runners. However, few trainers are aware of the $\dot{V}O_2$ slow component phenomena. Continuous work at $v\Delta 50$ allows less time to be spent specifically at $\dot{V}O_{2max}$, much less than during the 30/30 seconds light/heavy exercise intervals (3 minutes of time spent at $\dot{V}O_{2max}$ for $v\Delta 50$ versus 10 minutes in 18 ± 5 repetitions of 30/30 seconds). Moreover, the blood lactate response was more pronounced in the $\Delta 50$ run compared with the interval training (6.8 ± 2.2 *vs* 7.5 ± 2.1 mmol/L, respectively).

However, $v\Delta 50$ can be used for an intermittent protocol rather than a continuous one.[59] Demarie et al.[59] have demonstrated that lower level runners ($\dot{V}O_{2max}$ = 60 ml/min/kg) reached $\dot{V}O_{2max}$ at 92 ± 2% of $v\dot{V}O_{2max}$, a velocity between the onset of blood lactate accumulation and $v\dot{V}O_{2max}$ ($v50\%\Delta$). The long interval training was set at half the time to exhaustion at $v50\%\Delta$ as described previously by Billat et al.[13] for interval training at $v\dot{V}O_{2max}$. The recovery was active (50% $v\dot{V}O_{2max}$) and the work : pause ratio was 2/1. A time to exhaustion of 10:23 ± 1:26 min:sec ranging from 8 to 13 minutes for the continuous run at $v50\%\Delta$ was found. Hence, the exercise periods of the intermittent exercise ranged from 4:00 to 6:30 min:sec and the recovery periods from 2:00 to 3:15 min:sec. The sum of the exercise periods resulted in an average time limit of 19:38 ± 5:10 min:sec for the interval training. Runners performed 3 ± 1 repetitions of these long interval runs.

All participants showed similar $\dot{V}O_2$ kinetics, with maximal $\dot{V}O_2$ throughout all exercise periods. $\dot{V}O_{2max}$ was sustained for twice as long in this long interval training than in the continuous run at the same velocity ($v50\%\Delta$) [10:23 ± 5:51 *vs* 5:07 ± 3:03 min:sec for the intermittent versus continuous run, respectively]. Blood lactate accumulation was less in the intermittent (6.5 ± 2.2 mmol/L) versus the continuous run (7.8 ± 2.2 mmol/L). The authors concluded that intermittent training at a velocity which elicits a $\dot{V}O_2$ slow component (above the critical velocity or at a mid-way between vOBLA and $v\dot{V}O_{2max}$) can be used as an intensity to elicit $\dot{V}O_{2max}$ for long periods of time. Moreover, the individualisation of the duration of the repetition avoids early blood lactate accumulation. The average duration was, on average, 5 minutes at 92% $v\dot{V}O_{2max}$ with a recovery of 2:30 at 50% $v\dot{V}O_{2max}$.

However, this is probably not sufficient to elicit $\dot{V}O_{2max}$ in high level runners where shorter and higher velocity interval training may be preferable.[19,76]

3.1.3 Interval Training to Estimate Performance

Interval training can be used to estimate performance. In 1997, Babineau and Léger[77] reported that performance over 5000m was well predicted by the maximal cruising speed on a 6 × 800m run (30 seconds rest). Maximal cruising speed was the highest average speed that could be maintained over all of the work intervals in a single training session. For both runners and multi-sports participants, 6 × 800m interval training was more closely correlated with performance [the recovery between repetitions (r) = 0.95, p < 0.001, n = 23] than 12 × 400m (15 seconds rest) [r = 0.90, p < 0.001, n = 23] and 3 x 1600m (60 seconds rest) [r = 0.93, p < 0.001, n = 23]. Total distance run was always 4800m and the work : pause ratio was equal to 5. For runners only, the cruising speed over 1600m corresponded to the specific velocity during the 5000m run. This study was adapted to trainer's methods which uses the target specific velocity of the competition (those of the last season to target those for the present season) as a reference.

3.2 Long Term Effects of Aerobic Interval Training

3.2.1 Long Term Effects of Short Aerobic Interval Training

In some cases short interval training has been considered to be less effective in enhancing $\dot{V}O_{2max}$. The effectiveness of the different types of interval training has been compared: short (30 to 40 repetitions of 15 seconds work, 15 seconds rest) versus long (4 to 6, 4 minutes work, 2 minutes rest) performed at 130 and 115% of $v\dot{V}O_{2max}$, respectively, for recreational runners (54.8 ± 3.0 ml O_2/kg/min).[78] The third kind of training was continuous distance running at 90% v$\dot{V}O_{2max}$ for 20 to 30 minutes. The total duration of the different types of training (performed by 3 paired groups, 3 days per week over a 6 week period was similar. The $\dot{V}O_{2max}$ improvement was significantly higher for the long interval training and the continuous running (+6%) versus the short interval training (+3.6%). This could be because of the fact that complete rests were used that prevented $\dot{V}O_2$ reaching $\dot{V}O_{2max}$ in the short interval training. Moreover, the continuous running was performed at a high velocity (90% of v$\dot{V}O_{2max}$ making them reach 92.5% $\dot{V}O_{2max}$) to induce a $\dot{V}O_2$ slow component and increase $\dot{V}O_2$ towards $\dot{V}O_{2max}$.[59] In addition to this intense programme, runners had slow-pace runs at 78% of maximal heart rate (HR_{max}). The greatest improvement was in the time limit at 85% of the pretraining (80% post-training). The largest increase was seen in the continuous run group where time to exhaustion increased by 94% from 35 to 68 minutes; for long interval training time increased by 67% and for short interval training time to exhaustion increased by 65%. The continuous run seems to be more effective in enhancing both $\dot{V}O_{2max}$ and endurance at a submaximal velocity; however, this probably comes from the inactive rest used in the interval training. Submaximal $\dot{V}O_2$ at the same velocity (85% $\dot{V}O_{2max}$ of pretraining value) was decreased in relation to ventilation. Blood lactate measured at the end of the submaximal run was decreased from 6.6 ± 0.4 to 5.1 ± 0.3 mmol/L after training.

This study clearly showed that moderately trained recreational runners can improve both running economy and $\dot{V}O_{2max}$ within a relatively short period (6 weeks) by exchanging parts of their conventional aerobic distance training with more intensive distance or long interval training. A reduced pulmonary ventilation following training correlated significantly with the improved running economy, suggesting that ventilatory adaptation may contribute to the improved running performance. Other potential factors such as percentage of type I fibres in the vastus lateralis muscle, stride length, stride frequency and/or respiratory exchange ratio during submaximal run were unaltered with training.[78]

In 1971, Davies and Knibbs[79] insisted that to effect an improvement in $\dot{V}O_{2max}$ an individual must be prepared to work at or close to their $\dot{V}O_{2max}$ for prolonged periods of time, and even then improvement might be disappointingly small. Recently, in his training book for running, Daniels et al.[28] shared this point of view. This is especially important for previously trained runners compared with untrained individuals; even for untrained individuals, $\dot{V}O_{2max}$ was stable after 4 weeks of training and did not increase until the eighth week (end of training).[28]

Interval training was more effective for increasing rates of fatty acid oxidation than continuous training, despite lower total energy expenditure. With continuous training, the relative increase in rates of respiration with pyruvate and palmityl-carnitine were equal, implying that the activity of enzymes involved exclusively in pyruvate oxidation (i.e. pyruvate dehydrogenase) increased in proportion to those involved in fatty acid oxidation (i.e. enzymes of β-oxidation). In contrast, with interval training, the relative increase in the rate of respiration was greater with palmityl-carnitine, compared with pyruvate, implying that activity of enzymes involved in fatty acid oxidation increased to a greater extent than those involved in pyruvate oxidation. Indeed, adaptations of the β-oxidation pathway are most likely induced with exercise that promotes the use of fats and a high flux rate for fatty acids. Interval training may promote these conditions.[80] This confirms the hypothesis proposed 20 years earlier by Essen[44] and Essen et al.[45]

With repeated high intensity bouts (close to p$\dot{V}O_{2max}$), lactate and citrate may inhibit glycogenolysis during later bouts, resulting in an increased reliance on fatty acid oxidation.[45] Essen et al.[45] have used 60 minutes of intermittent intense exercise, 15 seconds work at v$\dot{V}O_{2max}$ and 15 seconds rest, compared with 60 minutes of continuous exercise at a load (mean 157W) i.e. 50% of $\dot{V}O_{2max}$ selected to yield the same integrated $\dot{V}O_2$. Thus, the same total amount of work was performed during both types of exercise. She demonstrated that at similar high workloads less glycogen is utilised and lipids contribute more to oxidative metabolism when exercise is performed intermittently (15 seconds work, 15 seconds rest) than continuously. The overall metabolic response to intermittent exercise is more similar to continuous exercise at about half the load than at an equally high workload. Therefore, high intensity interval training resulted in a smaller depletion of glycogen and a larger depletion of intramuscular triglycerides compared with low intensity continuous stimulation. With the interval training a repeated stimulation of fatty acid oxidation might have led to an up-regulation of this pathway, resulting in a greater stimulation of mitochondrial respiration in the presence of fatty acids.[80]

Henriksson and Reitman[80] showed that interval training (5×4 minutes at 10% $\dot{V}O_{2max}$ with a rest of 2 minutes in between) enhances the oxidative capacity of type II fibres compared with a continuous exercise of the same duration performed at 79% of $\dot{V}O_{2max}$. These data are interesting for middle-distance runners who have more type II fibres with a high oxidative capacity. However, only continuous training improved the whole body $\dot{V}O_{2max}$ (+12%, $p < 0.01$).

Tabata et al.[81] reported that supramaximal exercise (8×20 seconds at 170% $\dot{V}O_{2max}$ with a 10-second rest) enhances $\dot{V}O_{2max}$ after 7 weeks where individuals ($\dot{V}O_{2max}$ 53 ml/min/kg) carried out 5 training sessions in 5 days. This very short interval training (less than 5 minutes of effective work) allowed them to increase both maximal accumulated oxygen deficit, an indicator of the anaerobic capacity (+28%) and $\dot{V}O_{2max}$ (+13%).[81] The very short pause means that the average power output is still very high (115% $\dot{V}O_{2max}$) and allows $\dot{V}O_2$ to increase to $\dot{V}O_{2max}$ as demonstrated 1 year later by the same authors.[82]

3.2.2 Long Term Effects of Long Aerobic Interval Training

As seen in section 3.1, 2 longitudinal studies[64,65] calibrated the long interval training with reference to the time limit at $v\dot{V}O_{2max}$ and have reported a rapid increase of $v\dot{V}O_{2max}$ (4 week, 2 interval training sessions per week) with no decrease in the time spent (post-training) at $v\dot{V}O_{2max}$. Good level runners increased their $v\dot{V}O_{2max}$ from 20.5 ± 0.7 to 21.1 ± 0.8 km/h ($p = 0.02$) after 4 weeks of 1 interval training sessions at $v\dot{V}O_{2max}$ per week consisting of $5 \times 50\%$ of t_{lim} at $v\dot{V}O_{2max}$ with a work : active recovery ratio of 1/1. Recovery was run at 50% $v\dot{V}O_{2max}$. The second intensive training was performed at the maximal blood lactate steady state: 2 $\times$ 20 minutes with a work : active recovery ratio of 4/1, that is, 5 minutes at 60% $v\dot{V}O_{2max}$.[65]

The duration of interval training at $v\dot{V}O_{2max}$ can be longer: 60 and 75% of the time limit at $v\dot{V}O_{2max}$.[64] Using this interval training protocol 2 times per week, the performance over 3000m, $v\dot{V}O_{2max}$, $\dot{V}O_{2max}$ and time limit at the previous $v\dot{V}O_{2max}$, increased after only 4 weeks.[64] As in the study of Billat et al.,[64] Smith et al.[65] used a work : rate ratio of 1 and recovery was run at 60% of $v\dot{V}O_{2max}$. The third training session was a recovery session: 30 minutes at 60% of $v\dot{V}O_{2max}$. In good level athletes it may not be necessary to use such long interval durations since in less than 2 minutes,[33] oxygen reaches $\dot{V}O_{2max}$ when they run at $v\dot{V}O_{2max}$, and the time limit at $v\dot{V}O_{2max}$ is higher than 4 minutes.[83] Smith et al.[65] tested runners with performances of 10 minutes over 3000m, i.e. a middle level runner. It has been reported that oxygen kinetics is accelerated with training.[73,84,85] Using an individualisation of the duration of interval training with reference to the time limit at a given velocity allows the athlete to run the same number of repetitions (5) despite the great intervariability of the time limit of the continuous exercise.[13]

Importantly, the performance improvement in all individuals in the study by Smith et al.,[65] was uniform despite the heterogeneity (high coefficient of variation) of $v\dot{V}O_{2max}$ (18 to 22.7 km/h) and performance over 3000m (9 to 11 minutes). Therefore, for coaches with a group of runners with heterogeneous levels, it may be useful to apply the time limit to calibrate interval training work duration.

Burke et al.[86] demonstrated that if the exercise intensity is the same (95% $\dot{V}O_{2max}$), interval training enhances $\dot{V}O_{2max}$ (+7%) and blood lactate velocity (+25%). These changes appear to be independent of the length of the interval (30 seconds or 2 minutes with a work : pause of 1). However, these results were obtained in 21 female physical education students having only 40 and 43 ml/min/kg, respectively before and after the training period of 7 weeks at 4 times a week. The blood lactate threshold velocity increased from 64 to 78% $\dot{V}O_{2max}$.

It may be reasonable to assume that the high $\dot{V}O_2$ obtained during some forms of intermittent training leads to a significant stress on the aerobic system and results in the large increase in $\dot{V}O_{2max}$.[46,52,82] However, it may be possible, as demonstrated by Billat et al.,[64] that $v\dot{V}O_{2max}$ increases because of the decrease of running economy and not of $\dot{V}O_{2max}$, especially with athletes who already have a good level of $\dot{V}O_{2max}$ (above 70 ml/min/kg). Even if interval training taxes $\dot{V}O_{2max}$, the increase in $\dot{V}O_{2max}$ is not certain. To have some chance of increasing $v\dot{V}O_{2max}$, in this case, the distance run at a high velocity may be a determinant for $v\dot{V}O_{2max}$ and performance improvement,[87] since $v\dot{V}O_{2max}$ is related more to performance than $\dot{V}O_{2max}$.[7] However, as previously demonstrated by Fox's group[88,89] almost 30 years ago, it is more important to obtain improvement in $\dot{V}O_{2max}$ intensity than distance.[90]

3.2.3 Hypoxaemia Induced by Exercise and Interval Training

Maximal interval training has been shown to contribute to the development of arterial oxygen desaturation (hypoxaemia)[91] and less hyperventilation during heavy exercise.[92] However, some athletes with high $\dot{V}O_{2max}$ do not develop arterial desaturation during heavy exercise.[93] Interval training was performed for 12 weeks (4 days/week) on a cycle ergometer at 100% $\dot{V}O_{2max}$ for 3 minutes with 2 minutes of active recovery (50% $\dot{V}O_{2max}$). $\dot{V}O_{2max}$ was increased from 50.9 ± 5.6 to 61.6 ml/min/kg (+19%) whereas maximum expiratory volume (VE_{max}) increased only slightly during the early weeks of training. Moreover, interval training also induced lower alveolar partial pressure (PAO_2) and less hyperventilation during heavy exercise. Half of the reduction in arterial oxygen saturation (SaO_2) with interval training can be accounted for by the variation in ventilation. As hypothesised by Dempsey,[93] this suggests that there is little adaptability in the pulmonary system to physical training for several months even if the enhancement of maximal aerobic power is huge.

4. Conclusion

In conclusion, as stated by Astrand and Rodahl[46] 'it is an important but unsolved question which type of training is most effective: to maintain a level representing 90% of the $\dot{V}O_{2max}$ for 40 minutes, or to tax 100% of the $\dot{V}O_2$ capacity for about 16 minutes'. Today, this is still an open question. Before beginning longitudinal studies to try to answer this question, it is important to determine the metabolic response solicited by the different interval training protocols used by trainers.[26]

Even if optimal improvement in cardiorespiratory fitness is thought to occur from training at an intensity corresponding to 90 to 100% of $\dot{V}O_{2max}$,[46] this central factor of performance is not the only one to induce its improvement. Consequently, time spent at $\dot{V}O_{2max}$ is not the only parameter to be taken into account to judge the efficiency of a certain pattern of interval training on the improvement of $\dot{V}O_{2max}$ and performance.

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