Maximal Oxygen Uptake and Aerobic-Anaerobic Transition on Treadmill and Bicycle in Triathletes

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Abstract The maximal aerobic capacity and the aerobic-anaerobic transition were analyzed on 14 triathletes performing an incremental work load on a bicycle ergometer and on horizontal or inclined treadmills. To compare the cardiorespiratory responses between cycling and running, the subjects were divided into 2 groups of 7 with similar aerobic capacity determined from cycle runs. The first group ran on horizontal treadmill while the second group performed similar exercise on inclined treadmill at constant grade (1.5%). Heart rate was recorded by electrocardiogram. Oxygen uptake ($\dot{V}_{O_2}$), CO_2 production ($\dot{V}_{CO_2}$), respiratory frequency, and pulmonary ventilation were monitored at 30 s intervals through a Rudolph valve connected to a calibrated Oxycon V. Tidal volume, respiratory exchange ratio, equivalent O_2 and CO_2 were calculated from on-line computer. Aerobic and anaerobic thresholds were determined by a non-invasive method from pulmonary ventilation curves. The results showed that maximum oxygen uptake ($\dot{V}_{O_{2max}}$) did not differ between the 2 types of ergometers. Pulmonary ventilation, heart rate and $\dot{V}_{O_2}$ recorded at aerobic and anaerobic thresholds depended on the mode of exercise and reached the highest values on inclined treadmill. The amount of muscle mass, the type and the distribution of active motor units involved in each exercise test might be at the origin of these differences. This indicates that, when assessing a training program from anaerobic threshold values, it is necessary to take into consideration the type of ergometer used and the protocol performed.

Key words: triathletes, maximal aerobic capacity, treadmill, bicycle, anaerobic threshold.

Measurement of maximal aerobic capacity ($\dot{V}_{O_{2max}}$) is frequently used in athletes because it is recognized as being the best indicator of performance in

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endurance races. $\dot{V}_{O_{2max}}$ is commonly evaluated from protocol tests using a bicycle ergometer or treadmill. However, the cardiorespiratory mechanisms differ between these two modes of exercise and several studies have shown that $\dot{V}_{O_{2max}}$ levels were greater using a treadmill than a bicycle [1–5]. Glassford *et al.* [4] reported values 8% higher for $\dot{V}_{O_{2max}}$ determined from inclined treadmill compared to exercise on a bicycle. A difference in favor of the treadmill was also found by Chase *et al.* (15%) [5] and by Faulkner *et al.* (11%) [3]. On the contrary, Davis *et al.* [6] observed the reverse while Åstrand and Saltin [7] did not find significant difference in the aerobic capacity of trained subjects during maximal running or cycling. Similarly, Kohrt *et al.* [8] demonstrated that triathletes reached nearly identical $\dot{V}_{O_{2max}}$ in the two modes of exercise (the cycling $\dot{V}_{O_{2max}}$ being 95.7% of the running; $p > 0.05$) but pointed out that this evidence was not conclusive until further studies had been carried out on well-controlled training subjects. The discrepancy between these results can be explained by the physical aptitude of the subjects [9] or the sports practised [10–15].

Another important indicator of performance is the anaerobic threshold defined by Wasserman *et al.* [16]. This threshold for which blood lactate concentration is assumed to be of 2 mmol/l [17] indicates the upper limit of aerobic metabolism. Accumulation of lactate in the blood is positively related to the work load intensity and can limit the exercise. At a given work rate, the fitter the subject, the lower the lactate level [17, 18]. This anaerobic threshold can be determined by a non-invasive method based on the different response patterns of pulmonary ventilation, and analysis of expired flow gases [16]. As shown by Kindermann *et al.* [17], well-trained athletes, running on a treadmill at a constant gradient, can maintain exercise for a long period of time despite that the work load intensities were markedly above the anaerobic threshold of 2 mmol/l. As a consequence, these authors have proposed new concepts of threshold to determine work load intensities for training: an aerobic threshold (formerly the anaerobic threshold of Wasserman *et al.* [16]) and an anaerobic one for which the blood lactate concentration is approximately 4 mmol/l. To our knowledge, there is only a limited number of studies analyzing the influence of the modalities of testing training conditions on these thresholds. Davis *et al.* [6] analyzed anaerobic threshold and maximal aerobic power for arm cranking, leg cycling and treadmill running in untrained subjects. No significant difference was found between these three modes of exercise whereas Wiswell *et al.* [20] reported significantly greater anaerobic thresholds on treadmill than on bicycle. Withers *et al.* [10] pointed out in endurance trained cyclists and runners that cyclists reached higher anaerobic threshold than runners on bicycle while runners attained higher anaerobic threshold than cyclists on the treadmill. These authors concluded that the anaerobic threshold was influenced by the sports practised.

The aim of the present study was to examine the cardiorespiratory responses observed at aerobic and anaerobic thresholds during maximal exercise with different standard procedures including cycling and running on horizontal or inclined

treadmill in triathletes. The present study involved subjects well-trained in all events to discard a possible influence of the level of training and adaptation in one specific exercise. Similar experiments have been previously performed [8] but the authors only analyzed the maximal values of physiological responses during cycle ergometry, tethered swimming and running treadmill.

METHODS

Procedure. Fourteen male triathletes volunteered for the study after being fully informed of the nature, the risks and benefits of their participation; they gave their written consent. Their physical characteristics are given in Table 1. All have experienced triathlon competition for at least 3 years and participated regularly in national competition. They continued to train during the course of the experiment and they were familiarized with the experimental routine and the laboratory equipment: for at least 2 years, the subjects participated several times in similar laboratory sessions before the start of the experimental runs to determine their physical aptitude and to control their training program.

The subjects performed an incremental exercise on a bicycle ergometer (BE) (Jaeger ER 900) equipped with racing handlebars and toeclips. The cycle was constructed in such a way that rate of work was independent of the cycling frequency. After 5 min in resting position, the work load was increased by 50 W

Table 1. Physical characteristics of the subjects.

	Subj.	Age (year)	Ht (m)	Wt (kg)
Group I	1	19	1.82	76
	2	23	1.73	75
	3	24	1.80	73
	4	25	1.85	92
	5	28	1.71	62
	6	23	1.78	85
	7	27	1.74	66
	$\bar{X} \pm \text{SD}$	24 ± 3	1.77 ± 0.05	75 ± 10
Group II	8	19	1.79	69
	9	27	1.76	71
	10	25	1.79	75
	11	25	1.71	70
	12	28	1.82	76
	13	26	1.86	73
	14	26	1.71	70
	$\bar{X} \pm \text{SD}$	25 ± 3	1.78 ± 0.05	72 ± 3

Ht, body height; Wt, body weight. Mean value ($\bar{X}$) $\pm$ 1 standard deviation (SD) are indicated.

every 3 min until the exhausted subject could not continue. Verbal encouragements were given towards the end of the maximal exercise. The tests were always performed in the morning 2 h after a light breakfast. This procedure permitted evaluation of the maximum aerobic capacity of each individual.

To compare the cardiorespiratory responses between cycling and running, the subjects were divided into 2 groups of seven persons with similar maximal aerobic capacity determined from cycle runs. The first group ran on horizontal treadmill (HTR) (Jaeger, Lanfergotest) throughout the entire period of the test. After a resting period (5 min), the speed of the motor-driven treadmill was set at 6 km/h then increased linearly 1 km/h each 2 min. The second group performed the same exercise but on inclined treadmill (ITR), at constant grade (1.5%). For this selected grade there was a good relationship between physiological parameters recorded during field experiments and laboratory runs [21]. Each subject was strongly encouraged to perform an effort leading him to physical exhaustion. The tests were carried out in the morning in similar experimental conditions as for the bicycle.

Each session was always separated by 2 d during which the athletes carried out their usual activities at home and their training programs but without heavy work load intensity. Subjects participated in only one experiment a day.

The following physiological measures were monitored at 30 s intervals: Heart rate (HR) from electrocardiogram (Marquette, case 15); Oxygen uptake ($\dot{V}_{O_2}$), CO_2 production ($\dot{V}_{CO_2}$), respiratory frequency (f), and pulmonary ventilation ($\dot{V}_E$) were measured with the subjects breathing through a Rudolph valve connected to a calibrated Oxycon V (Mijnhart, MSR). Analyzers were calibrated with standard gas mixture before each run. Each standard gas was also controlled on mass Spectrometer (Perkin-Elmer). Tidal volume (V_T), respiratory exchange ratio, equivalent O_2 (V_{eqO_2}) and CO_2 (V_{eqCO_2}) were calculated from an on-line computer.

Blood lactate concentration was measured by spectrophotometry (Beckman, type UV 25) using an enzymatic method. Arterialized blood was sampled from an ear lobe at aerobic and anaerobic thresholds and 2 min after the end of each exercise [22]. In treadmill tests, it was not possible to sample blood on running athletes at aerobic and anaerobic thresholds. Consequently only blood lactate concentrations measured at the end of exercise were reported in the present study.

Calculations. Aerobic and anaerobic thresholds were determined by a non-invasive method taking into account the response patterns of different ventilatory parameters [17]. The threshold points were automatically detected from linear regressions fitted on to pulmonary ventilation curves by a least square mathematical method. A typical example of pulmonary ventilation related to time is shown on Fig. 1 for a cycling subject. The aerobic (AT) and anaerobic (ANT) thresholds can be identified by the inflexion points of nonlinear increases in the curves of $\dot{V}_E$. The disruption points of the relationships between time and V_{eqO_2} and V_{eqCO_2} were also taken into account. The aerobic and anaerobic thresholds correspond to the first and the second curve disruptions, respectively. These thresholds delimitate

Fig. 1. Pulmonary ventilation as a function of time. The times at which arterialized blood was sampled for blood lactate determination are indicated by symbol L. Aerobic (AT) and anaerobic (ANT) thresholds are defined from curve disruptions.

three phases: 1) a transient aerobic phase comprised between the beginning of the exercise and the aerobic threshold; 2) a transition phase between aerobic and anaerobic thresholds; 3) a mainly anaerobic phase between anaerobic threshold and the end of exercise.

Maximal cardiorespiratory variables corresponded to the highest values attained at the end of exercise during an interval of at least 30 s.

Pairwise *t*-tests were used for intra-group comparisons: Bicycle BE1 (group 1) vs HTR and BE2 (group 2) vs ITR. Student's *t*-tests for independent variables were used for inter-group comparisons: BE1 vs BE2 and HTR vs ITR. At aerobic and anaerobic thresholds, when variables were expressed as percentage of maximal levels, the data were tested after an arc sine transformation ($\phi = 2 \arcsin \sqrt{x}$) in order to stabilize the variance [23]. 0.05 was accepted as significant level.

All values given are mean ($\bar{X}$) $\pm$ 1 standard deviation (SD).

RESULTS

Maximum aerobic power

Figure 2 shows the mean values of relevant cardiorespiratory parameters for the two groups of subjects and for each exercise tests. All data corresponded to exhaustive exercises. During maximal exercise on bicycle ergometer, there were no significant inter-group differences for the parameters considered, demonstrating

Fig. 2. Mean maximal value $\pm$ SD (vertical bars) of pulmonary ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}O_2$), respiratory frequency (f), and heart rate (HR) at the end of each exercise tests. Hatched columns represent the data obtained from inclined treadmill (1.5); * $p < 0.05$; ** $p < 0.01$.

that the cardiorespiratory responses were homogeneous for the 2 groups of subjects. This indicates similar levels of physical fitness.

During maximal cycling, the mean value of oxygen uptake was 66.4 ± 1.0 ml/(min·kg) for the 1st group and 66.9 ± 6.9 for the 2nd group. These values did not differ significantly from those obtained by maximal treadmill running (66.1 ± 7.9 and 66.9 ± 7.4 ml/(min·kg) for HTR and ITR, respectively). For cycling, $\dot{V}_{\text{CO}_2}$ was always higher than for running ($p=0.039$ for HTR and $p=0.024$ for ITR).

Pulmonary ventilation was significantly lower in running than in cycling subjects (BE: 170.0 ± 20.4 vs HTR: 140.3 ± 43.6 l/min, $p=0.017$ and BE: 183.0 ± 19.5 vs ITR: 170.8 ± 12.5 l/min, $p=0.027$). Compared to horizontal treadmill, $\dot{V}_E$ recorded in tests on inclined treadmill tended to increase (+21.7%) without reaching statistical significance ($p=0.052$). $\dot{V}_E$ increments can be explained by concomitant increases in f and $\dot{V}_T$.

Heart rate values were not significantly different between subjects tested on horizontal treadmill (186 ± 9 beats/min) and on bicycle ergometer (184 ± 6 beats/min). However, running uphill was more stressful than cycling since HR was significantly elevated (180 ± 12 vs 185 ± 12 beats/min, $p=0.002$).

At the end of the exercise, blood lactate concentrations were always lower in treadmill tests (HTR: 10.9 ± 1.2 , $p=0.022$; ITR: 13.4 ± 2.0 mmol/l, $p=0.05$) than in bicycle tests (14.4 ± 2.4 and 16.6 ± 3.4 mmol/l). The blood lactate concentrations were higher on the inclined treadmill than on the horizontal treadmill ($p=0.017$).

Finally, the maximal running speeds were not different between the two test procedures (HTR: 18.8 ± 0.9 vs ITR: 19.1 ± 2.1 km/h). Duration of exercise was longer on treadmill (HTR: 29.2 ± 2.4 ; ITR: 29.6 ± 4.1 min) than on bicycle (BE1: 26.1 ± 2.6 ; BE2: 26.0 ± 1.6 min) ($p=0.010$ for HTR and $p=0.017$ for ITR).

Aerobic-anaerobic transition

Mean values of cardiorespiratory data recorded at aerobic and anaerobic thresholds are shown in Figs. 3 and 4. Statistical analyses performed on absolute values or on data expressed as percentage of maximal levels led to similar conclusions. As for maximum aerobic power, statistical analyses did not reveal differences between the 2 groups of cycling subjects.

Aerobic threshold. Figure 3 points out that there are significant differences in $\dot{V}_E$, f , $\dot{V}_{\text{O}_2}$ and HR between running and cycling subjects at aerobic threshold. Compared to cycling, running on a treadmill increased $\dot{V}_E$ (HTR: $p=0.015$; ITR: $p=0.001$). This was accounted for by both increased f and $\dot{V}_T$ except for inclined treadmill for which f was significantly increased ($p=0.001$) while $\dot{V}_T$ was unchanged. Running on inclined treadmill increased $\dot{V}_E$ by 23.6% ($p=0.045$).

Oxygen uptake was significantly affected by the modalities of exercise but only when considering the inclined treadmill for which $\dot{V}_{\text{O}_2}$ exceeded that of bicycle by 19% ($p=0.005$) and that of horizontal treadmill by 21% ($p=0.006$). Inclined treadmill significantly increased $\dot{V}_{\text{CO}_2}$ when compared to bicycle ($p=0.002$) or to horizontal treadmill ($p=0.004$).

Fig. 3. Mean value $\pm$ SD (vertical bars) of pulmonary ventilation ($\dot{V}E$), oxygen uptake ($\dot{V}O_2$), respiratory frequency (f), and heart rate (HR) at aerobic threshold. Hatched columns represent the data obtained from inclined treadmill (1.5); * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Heart rate scored highest ($p < 0.044$) when measured in treadmill tests (135 ± 9 and 133 ± 15 beats/min for bicycle vs 145 ± 15 and 149 ± 13 beats/min for HTR and ITR, respectively). No significant effect of the inclination of the treadmill appeared.

The time at which aerobic threshold was reached was significantly greater ($p = 0.021$) for ITR (17.1 ± 3.6 min) than for HTR (14.5 ± 2.5 min). No significant

Fig. 4. Mean value $\pm$ SD (vertical bars) for pulmonary ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}_{O_2}$), respiratory frequency (f), and heart rate (HR) at anaerobic threshold. Hatched columns represent the data obtained from inclined treadmill (1.5); * $p < 0.05$; ** $p < 0.01$.

difference was found between running and cycling.

Anaerobic threshold. Cardiorespiratory variables elicited at anaerobic threshold are shown in Fig. 4. For running uphill, $\dot{V}_E$ was larger than on bicycle (+11.6%; $p = 0.003$). This increase was mainly accomplished by an increment in breathing frequency ($p = 0.014$), V_T remaining constant. A positive effect of the treadmill grade was observed on $\dot{V}_E$ (+10.2%; $p = 0.018$).

Compared to bicycle, the triathletes required an average $\dot{V}_{O_2}$ of about 7% less when the test was performed on horizontal treadmill ($p=0.035$). The reverse was seen in inclined treadmill test ($+7\%$; $p=0.023$). Running on inclined treadmill increased anaerobic threshold $\dot{V}_{O_2}$ ($+13\%$; $p=0.002$). Bicycle $\dot{V}_{O_2}$ were midway between horizontal and inclined treadmill values. For $\dot{V}_{CO_2}$, no significant difference was found between BE and HTR or ITR. Compared with HTR, running uphill increased significantly $\dot{V}_{CO_2}$ ($+29\%$; $p=0.002$).

As reflected by heart rate, for submaximal exercises, running uphill engendered more stressful strain than cycling. When comparing these two modes of work the difference in HR value was 10 beats/min ($p=0.019$) in favor of the runners.

The time at which anaerobic threshold was reached was not significantly different between cycling (BE 1: 20.8 ± 2.3 ; BE 2: 21.7 ± 1.4 min) and running (HTR: 22.9 ± 2.3 ; ITR: 24.8 ± 4.0 min).

DISCUSSION

Maximum aerobic power. Compared with the literature, the most striking finding of the present study is that $\dot{V}_{O_{2max}}$ is very similar between the different exercise modalities as applied here. This does not agree with numerous studies [1–5] pointing out that treadmill elicited a greater $\dot{V}_{O_{2max}}$ than cycle ergometer. This discrepancy can be related to the specificity of training due to local adaptation of active muscles which can induce a difference in mechanical work efficiency. In the present study, the triathletes exercise on bicycle and treadmill ergometers and use muscular masses which are regularly trained. As a consequence at maximal exercise, there is no difference in $\dot{V}_{O_{2max}}$. This observation supports the speculation that bicycle $\dot{V}_{O_{2max}}$ equal or closely approach treadmill values in individuals with previous experience of bicycling as a form of exercise [13]. In the same way, we confirm results showing that differences between running and cycling $\dot{V}_{O_{2max}}$ were reduced in triathletes well-trained in all events [8].

The present data stress that for triathletes, treadmill or bicycle ergometers can be recommended to evaluate their training state when $\dot{V}_{O_{2max}}$ is considered.

It also appears that the increased treadmill grade does not affect the level of $\dot{V}_{O_{2max}}$. Other studies comparing these responses have produced inconsistent results. Kasch *et al.* [24] hypothesized that the higher $\dot{V}_{O_{2max}}$ observed in uphill running could be due to the fast running rate and to the long duration of the tests used by other investigators. These two factors induce a greater muscle demand for oxygen. This is not supported by our data since the running speeds as well as the duration of the tests were similar between the 2 experimental runs on treadmill. It could be that the treadmill inclination (1.5%) was not great enough to induce an increase in $\dot{V}_{O_{2max}}$. Indeed, it has been previously reported [1] that $\dot{V}_{O_2}$ is related to the inclination of the ergometer but only for gradient of 5.25% or more.

Compared with running, the maximal aerobic capacity of cycling subjects was

mainly limited by the adaptation of heart capacity: in cycling, $\dot{V}_E$ can increase to a high level while heart rate remains unchanged or is lowered. This suggests that cycling mainly stresses the respiratory mechanisms. Review of the literature shows controversy on this issue. For Åstrand and Saltin [7], Hermansen and Saltin [1], Kohrt *et al.* [8], there is no significant $\dot{V}_E$ difference between running and cycling. For Pannier *et al.* [9], Potiron-Josse [15], treadmill $\dot{V}_E$ were larger than those for bicycle, for long-distance runners and sportsmen (soccer, rugby, and tennis players).

The greater degree of metabolic acidosis, as reflected by the level of blood lactate accumulation, could be at the origin of higher $\dot{V}_E$ observed during cycling. Such an effect acting through carotid body receptors has been previously described [25]. Other reasonable explanation refers to the fact that in cycling there is a greater strain on leg muscles inducing an increase in neurostimuli from proprioceptors. In contrast, for the treadmill test, the strain is more uniformly distributed over active muscle masses and the action of neural impulses is less powerful. This influence of stimuli of neurogenic origin initiated by vigorous contractions has been previously put forward [26] but remains to be demonstrated.

Aerobic-anaerobic transition. As pointed out in the introduction and METHODS sections, the aerobic and anaerobic thresholds correspond to those of Kindermann *et al.* These authors defined an aerobic threshold (anaerobic threshold of Wassermann *et al.* [16]) and an anaerobic threshold for which blood lactate concentration reached 4 mmol/l.

$\dot{V}_E$, HR, and $\dot{V}_{O_2}$ observed at anaerobic threshold depended on the mode of exercise and of the protocol performed.

The results show that the anaerobic threshold occurs at a significantly greater percentage of $\dot{V}_{O_{2max}}$ on inclined treadmill (88.8%) than on horizontal treadmill (79.0%) or on bicycle ergometer (83.3%). Similar observation has been reported by Wiswell *et al.* [20] who found a higher significant value (74.5% $\dot{V}_{O_{2max}}$) for inclined treadmill than for cycle (69.4%). Withers *et al.* [10] also reported in endurance trained athletes significantly greater anaerobic threshold on inclined treadmill (75.8% $\dot{V}_{O_{2max}}$) than on bicycle (63.8% $\dot{V}_{O_{2max}}$). Davis *et al.* [6] found the reverse (cycle: 63.8% $\dot{V}_{O_{2max}}$; inclined treadmill: 58.6% $\dot{V}_{O_{2max}}$) from experiments in untrained persons. This suggests that the mode of exercise and the level of training are important determinants of the anaerobic threshold.

The large values of anaerobic thresholds measured in the present experiment can be explained by the fact that the experiments were performed on elite athletes highly trained [27]. Kindermann *et al.* [17] also reported anaerobic thresholds reaching 85% $\dot{V}_{O_{2max}}$ in cross-country skiers of national level running on an inclined treadmill.

Contrary to maximal work loads, at submaximal exercise with the exception of horizontal treadmill, running $\dot{V}_E$ were greater than for cycling. If we assume from results observed at the end of exercise that cycling induces a greater acidosis than running, the relationship between metabolic acidosis and $\dot{V}_E$ seems to be less strong

than that observed at maximum work rate.

When considering treadmill apparatus, the inclination modifies $\dot{V}_{O_2}$ and $\dot{V}_E$ values while heart rate remained unchanged. This indicates that, in our experimental condition, only this criterion can be used to predict a training program from treadmill running test.

The amount of muscle mass but also the type and the distribution of active motor units involved in each exercise test performed in the present study might be at the origin of the differences observed between the different apparatus. Contrary to cycling, running on treadmill is a ballistic movement which implies brief trunk and upper limb contractions. These muscles represent a small amount of the total musculature involved in $\dot{V}_{O_2}$ but may modify the lactate clearance. When considering the treadmill apparatus, it seems possible that the inclination also influences the recruitment and the distribution of active motor units. Unfortunately no electromyographic comparisons between cycling and running subjects on horizontal and inclined treadmill were found in the available literature and the hypothesis involving recruitment of additional trunk and limb musculatures remains inconclusive.

In conclusion, the major finding of this study is that, for triathletes, it is possible to judge of the real value of $\dot{V}_{O_{2max}}$ either from bicycle ergometer or from treadmill tests. This can be explained because these athletes are trained in cycling and running which are forms of exercise used in the tests performed in the present study. As a consequence, a possible specific training effect on $\dot{V}_{O_{2max}}$ can be ruled out. However, the anaerobic threshold values are strongly related to the modes of ergometer used and particularly to the selected grade imposed during treadmill test. For anaerobic threshold determination, it can be recommended to take into consideration not only the form of ergometer but also the grade of treadmill to determine training program of endurance capacity.

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