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Estimation of the Contribution of the Various Energy Systems During Maximal Work of Short Duration

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Abstract

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The aim of this experiment was to estimate the relative contribution of the various energy delivery systems during maximal exercise tests of short duration. Twenty-five males were submitted to a $\dot{V}O_2$max test and 10-, 30-, and 90-s maximal ergocycle tests. Expiratory gases were collected with a Douglas bag during the entire 30-s test and continuously monitored with an open-circuit system during the 90-s test. Estimates of the phosphagenic component represented approximately 55%–60% of the energy expenditure during the 10-s work performance. Results of the 30-s test indicated that the relative contributions of the energy systems were 23%, 49%, and 28% for the phosphagenic, glycolytic, and oxidative pathways, respectively. For the 90-s test, these estimates were 12%, 42%, and 46% for the three metabolic systems. The highest contribution of each system during the 90-s was obtained from 5 to 15 s for the phosphagenic component, from 16 to 30 s for the glycolytic, and from 61 to 75 s for the aerobic energy systems. During the 90-s test, $\dot{V}O_2$max was reached after approximately 60 s. It is concluded that the 30 and 90 s are not strictly anaerobic although they all have a large anaerobic component.

Introduction

Physiologic and metabolic adaptations occurring during prolonged exercise have been extensively documented in the last 20 years. There is, however, relatively less information on the response of human subjects to maximal exercise of short duration. It is commonly agreed that short and intense bouts of exercise rely predominantly on the immediate (ATP-PC) and short-term (anaerobic glycolysis) energy production systems. The total amount of energy available from immediate and short-term energy sources is quite limited and is sufficient to meet the needs of exercise for only a few minutes. The maximal capacity of the immediate sources of energy in normal sedentary men has been estimated to be about 45 kJ with an estimated maximal power from about 300 kJ/min (2). These estimations, and others from Margaria et al. (12) and Di Prampero (6), assumed that the time to maximal contribution of the phosphagenic energy production system is about 6–8 s. The second anaerobic pathway, the glycolysis with lactate as end product, has an estimated power of about 150 kJ/min in normal men and a total capacity of about 200 kJ (2). Anaerobic glycolysis is activated, however, before the depletion of the phosphagenic reserves. Jacobs et al. (9) have demonstrated that muscle lactate concentration was 5–8 times the resting level after a 10-s supramaximal ergocycle test, an indication that glycolysis starts very early at the onset of maximal exercise. Moreover, McGilvery (14) has estimated that the rate of the glycolytic pathway was increased by a factor of about 1000 upon going from rest to maximum work over a period of 20 s. Finally, one has to take into account the fact that during maximal exercise of short duration, some ATP regeneration is achieved through substrate oxidation. Thus, the task of estimating the relative contribution of each energy system in currently used so-called anaerobic tests is a complex task and one that may require several assumptions. The purpose of this study was to estimate the contributions of the various energy production systems in three supramaximal ergocycle tests lasting 10, 30, and 90 s, respectively.

Methods

Subjects

Twenty-five male subjects gave their informed written consent to participate in this study as required by the Human Ethics Committee of the Institution. They were cross-country skiers, biathletes, and speed-skaters visiting our laboratory for routine evaluation.

Testing Procedures

Maximal oxygen uptake ($\dot{V}O_2$max) was assessed with an automated open-circuit system using O_2 and CO_2 analyzers (20–40 ms and 100 ms response time, respectively) (Applied Electrochemistry, Sunnyvale, USA), ventilatory volumes were determined using a pneumotachometer (Fleisch Type Hewlett-

Table 1 Characteristics of the subjects

	Tests		
	10-s	30-s	90-s
n	23	21	20
Age	20.6 ± 3.5[a]	20.3 ± 3.5	22.2 ± 3.7
Weight (kg)	69.4 ± 9.5	67.7 ± 7.7	70.5 ± 10.3
Height (cm)	176 ± 6	175 ± 5	176 ± 7
$\dot{V}O_2$max ($ml\ O_2/kg \cdot min^{-1}$)			
Ergocycle	64.9 ± 3.6 (n = 7)	64.9 ± 3.6 (n = 7)	61.8 ± 2.0 (n = 3)
Treadmill	67.0 ± 3.9 (n = 16)	67.0 ± 4.3 (n = 13)	66.7 ± 3.3 (n = 15)

[a] Mean ± SD

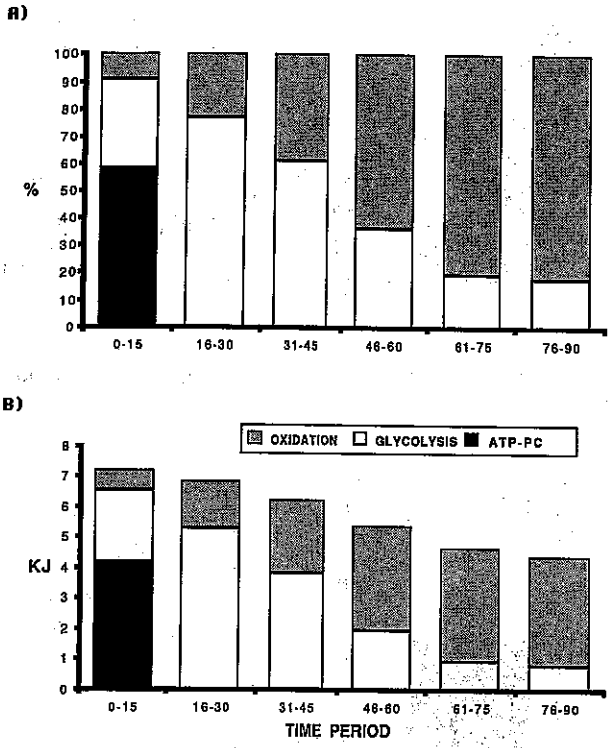

Fig. 3 Relative contribution of each metabolic pathway to work output in the 90-s test. (A) results in % of work output; (B) results in kJ.

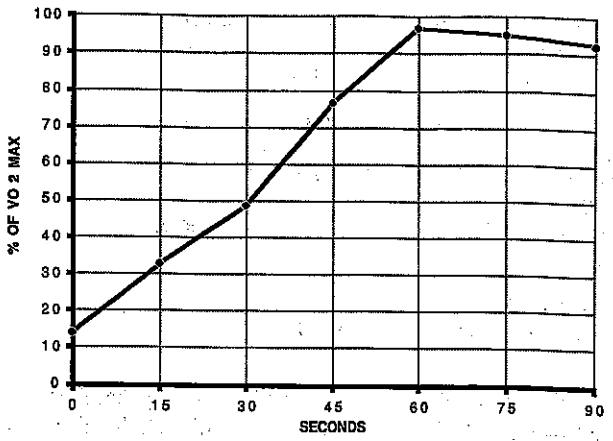

Fig. 4 Oxygen uptake during the 90-s test.

Table 3 Estimation of the mean power and capacity of the anaerobic energy systems

System	Power	Capacity
ATP-PC	12 W/kg[a]	60 J/kg
	840 Wb	4 kJ[b]
Anaerobic glycolysis	8 W/kg[c]	210 J/kg[d]
	560 Wb	15 kJ[b]

[a] Estimated in the 2nd s of the 10-s test
[b] For a normal man of 70 kg
[c] Estimated in the 16–30 th s time period of the 30-s test
[d] Estimated from the 90-s test

output during the three tests. During the 10-s test, the relative contributions of the various energy systems were estimated at 53%, 44%, and 3% for the phosphagenic, glycolytic, and oxidative pathways, respectively. These estimations were 23%, 49%, and 28% during the 30-s test and 12%, 42%, and 46% during the 90-s test for phosphagenic, glycolytic, and oxidative energy systems, respectively. Figure 3 illustrates the decrease in the power output as a function of time during the 90-s test as well as the shift between the various ATP production systems. The highest contribution of each system during the 90-s test was estimated to be in the first 15 s for the phosphagenic, from 16 to 30 s for the glycolytic, and from 61 to 75 s for the aerobic energy system. It is interesting to note that the oxidative pathways meet most of the energy needs as early as the 46th–60th s time period. At that time, about 64% of the total energy output is generated from the aerobic system. In the next time period (61th–75th s) and during the last 15 s of the test, the aerobic contribution represented 81% and 83% of the work output, respectively. During the last 30 s of the 90-s test, work output was predominantly achieved through the support of the aerobic energy system as peak VO_2 was reached and maintained. During this period, the subjects reached 95%–97% of their VO_2max (Fig. 4). Data indicated that the increase in oxygen uptake from the start to the 60th s was linear with time ($R = 0.996$. Estimates of maximal powers and capacities of the ATP-PC and anaerobic glycolysis systems for a normal man of 70 kg are presented in Table 3.

Discussion

Performances of the subjects of the present study were similar to those reported by several authors. Simoneau et al. (15) and Boulay et al. (3) had comparable results for the 10-s and the 90-s capacities while Boulay et al. (3) reported a similar range of power values in the 10-s test. Cheethman et al. (4) and Jacobs et al. (9) also reported similar power output (1–5 s) data during the 30-s test. Comparable results were also obtained by Bar-Or et al. (1) for the 30-s Wingate capacity test.

Anaerobic Nature of Tests

Maximal tests of short duration have generally been used to evaluate anaerobic capacity or power. Although the assumption of anaerobiosis is almost strictly met with performances lasting 5–10 s (8, 12, 15), it does not hold with tests lasting 50–90 s (5, 15, 18, 19). Thomson and Garvie (19) obtained an aerobic contribution of approximately 25% to the total energy production during a 30-s all-out running test. This result is similar to the 28% value measured in the present study during the 30-s test but much lower than the results reported by Stevens and Wilson (17). In a recent study, Kavanagh and Jacobs (11) reported an oxidative contribution of 18.5% in five subjects performing the Wingate test. Interindividual variation however was important (from 11.9% to 25.1%) and appeared related to the VO_2max of the subjects. Our results tend to support their conclusion that subjects with higher VO_2max had larger relative aerobic contributions because the subjects of the present study had a VO_2max of about 65 ml O_2/kg/min. Thomson and Garvie (19) reported a contribution of 67% for the total anaerobic (phosphagenic and glycolytic) sources during an all-out running test to exhaustion (mean running time of 65 s), which is slightly higher than the 54% value obtained during the 90-s test of this study. However, this difference may be explained (1) by a longer test in the present study and (2) by pacing during the first 20–30 s of the 90-s test (15). This ensured that the subjects were able to maintain a higher rate of work during the last seconds of the test. Unpublished data from our laboratory indicate that such a procedure did not significantly influence the total work output alt-

Table 2 Work capacity and power in the short duration tests

	Tests		
	10-s	30-s	90-s
Maximal power (W/kg)	12.1 ± 1.4[a]	9.8 ± 1.0[b]	–
Maximal capacity (J/kg)	108 ± 13	260 ± 28	493 ± 54

[a] Best second
[b] Average of the 1st–5th s time period

Packard, McMinville, USA) with a 5.3–1 mixing chamber and a microcomputer (Apple Computer, Cupertino, USA) during a progressive test either on a motor-driven treadmill (Quinton Instruments, Seattle, USA) or an electromagnetically braked ergocycle (Warren E. Collins, Braintree, USA). As expected, the ergocycle test gave slightly lower $\dot{V}O_2$max values than the treadmill test. Table 1 presents some physical and physiologic characteristics of these subjects. Three maximal tests of short duration were carried out on a modified Monark ergocycle (Monark-Crescent AB, Varberg, Sweden). After a 5-min warm-up period on the ergocycle, a 10-min mandatory and complete rest period was imposed before the first 10-s trial (15). After this first 10-s, a second 10-min rest period was granted before a second trial. A single 30-s trial (1) was performed 15 min after the second 10-s test. Finally, a 90-s test (15) was performed 20 min after the 30-s test. Initial work loads for these three tests were 0.09, 0.075, and 0.05 kp/kg for the 10-, 30-, and 90-s tests, respectively. Maximal capacities were expressed as the total work output (J/kg) during the best 10-s trial and during the 30-s and the 90-s tests. Maximal powers were expressed in W/kg. During the 30-s test, expiratory gases were collected with a Douglas bag and analyzed for fractional concentration of O_2 and CO_2. Volumes wre measured with a Tissot gasometer (Warren E. Collins, Braintree, USA). During the 90-s test, respiratory gases were analyzed every 15 s with the same open-circuit system as in the $\dot{V}O_2$max test.

Estimation of Each Energy Pathway Contribution

ATP-PC system. To facilitate calculations, estimates of the contribution from this ATP production system were based on three assumptions: (1) in the initial seconds (i. e., until the maximal power output was reached), all ATP was regenerated by the ATP-PC system and accordingly all work was attributed to this system (i. e., its contribution was assumed to be zero at the 11th s), (2) at such high power output, the contribution of this system to work output lasted approximately 10 s, and (3) after the occurrence of maximal power output (about 2–3 s) the decrement was linear. *Aerobic system.* The oxygen uptake during the 30-s and the 90-s tests was converted in kJ by a factor of 20.92 kJ/l O_2, assuming 100% carbohydrate oxidation (RQ reached .99 and 1.01 during the 30- and the 90-s tests, respectively), then adjusted for a mechanical efficiency of 16.2%, the average value achieved at the end of the $\dot{V}O_2$max test. The contribution of this system to the overall work output was assumed to begin in the second following the occurrence of maximal power output and to increase linearly until $\dot{V}O_2$max was reached. *Anerobic glycolysis.* The contribution of this system was derived by substrating the two previous estimates from the total power and work output.

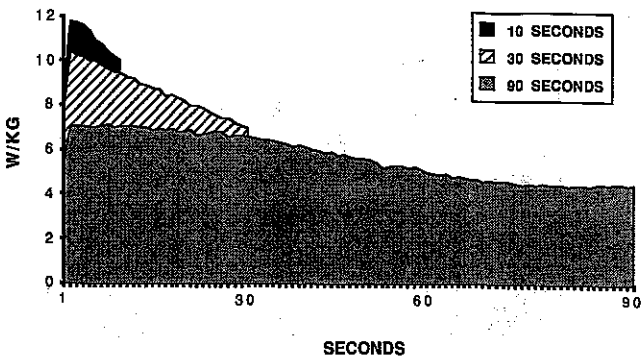

Fig. 1 Mean power output per second in the three short duration tests.

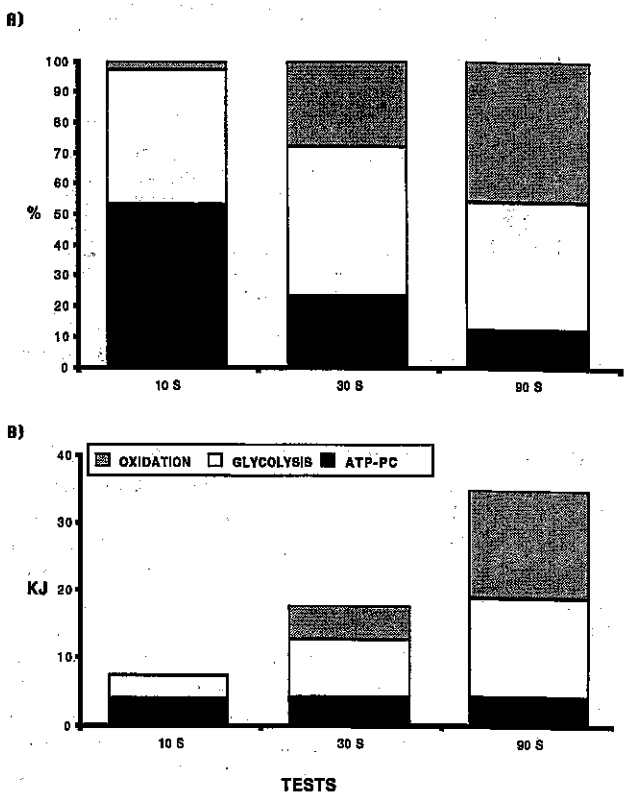

Fig. 2 Estimated contribution of the three metabolic pathways to work output in the three short duration tests. (a) results in % of total work output; (B) results in kJ.

Results

Table 2 gives the external power generated during the 10-s and the 30-s tests and the total work output over the duration of each of the three tests. As expected, maximal power was observed during the first few seconds of the 10-s test (i. e., between the 1st and the 3rd) and reached about 12 W/kg. Total work output during the first 10 s of the 30-s test reached about 90% of the work output obtained in the 10-s test. Figure 1 presents the mean power output at each second during the three tests. The differences between the 10-s performance and the first 10 s of the 30-s and the 90-s tests can be seen in this graph. During the 90-s test, power output during the last 20 s reached a plateau at about 4.5 W/kg. Figure 2 illustrates the estimated contribution of each energy production system to the power and the total work

hough the subjects perceived the test as a less unpleasant one. The linear increase in oxygen uptake with time indicates that the involvement of the oxidative energy production starts at the onset of exercise performance. This confirms the results of Thomson and Garvie (19) which indicated that O_2 consumption increased linearly over an all-out sprint during the first 45 s. On the other hand, Yamamoto (20) observed a plateau in O_2 uptake and work output after about 60 s during an all-out cycling test (lasting about 120 s). Results of the present study show that O_2 uptake also reached a plateau in the last 30 s of the 90-s test (at 95% and more of the $\dot{V}O_2max$) and that there was a plateau in the power output during the same period. Thus, it might be concluded that the oxidative pathways had the major contribution to ATP regeneration at that time. Our estimate is that after 60 s of very heavy work, over 80% of the work output is dependent on the oxidative energy production. Thus, we may conclude that during a 10-s test, almost the entire work output is sustained by the anaerobic pathways (about 97%). In the 30-s test, however, we observe a significant contribution from the oxidative sources (about 28%). Finally, work output during the 90-s test is sustained almost equally by oxidative and by phosphagenic and glycolytic systems.

Power of the Three Energy Systems

Yamamoto (21) suggested three optimal time zones for the estimation of alactic, lactic, and aerobic capacities, i. e., 1–10 s (or peak power at 3rd–6th s), 30–60 s, and after 60 s, respectively. Results of the present study are in agreement with this proposal for the alactic (phosphagenic) and oxidative energy production, but they indicate that the time zone of the maximal contribution of the glycolytic system is rather between the 16th and 30 th s. Results of the present study show that the estimated maximal power of the ATP-PC system was reached quite early in the 10-s test, as early as the 2nd or 3rd s in most subjects. Thus, recording of power output at each second is necessary to estimate the power of this system. The maximal power of the glycolytic pathway was reached during the 16- to 30-s period in the 90-s test. One can reasonably consider that the maximal power of this system was also reached in the same time interval during the 30-s test. In their study using electrical stimulation with occluded circulation, Hultman and Sjoholm (7) have shown that glycolysis reached its maximum between 40–50 s, while our estimates indicated a slightly earlier occurrence. This apparent discrepancy between the two studies might be caused by the occlusion of the circulation in Hultman and Sjoholm's work which increased reliance on glycolysis in absence of any oxidative metabolism. Because the depletion rate of phosphocreatine (PC) is very fast in the initial period of anaerobic work (16) and the glycolysis turnover rate is heavily enhanced in the same time period (14), recording of power output and O_2 uptake during a 30-s performance, such as the Wingate test, thus yields an interesting approximation of the power of the glycolytic pathway when combined with oxygen uptake data. Finally, maximal aerobic power ($\dot{V}O_2max$) was almost reached after 60 s in the 90-s test. In other words, the 90-s test can also be used to obtain a measurement of near $\dot{V}O_2max$ in spite of its short duration.

Phosphagenic and Glycolytic Capacities

Estimation of the total capacity of the phosphagenic system relies on assumptions described earlier. Hultman and Sjoholm (7) and Sjoholm et al. (16) measured PC concentrations during electrical stimulation of quadriceps muscle after occlusion of the circulation. PC concentrations decreased 36% during the first 10 s, and estimation of ATP accounted for by this PC utilization reached about 60%. Even though the circulation was not occluded in our study, the relatively negligible contribution of the oxidative system during this short period make both situations quite comparable. With the assumptions mentioned in the methods section, we estimate that the phosphagen pool contributes about 53%–60% of the work output during the 10-s test. The capacity of the glycolytic system, on the other hand, can be estimated from the results obained in the 90-s test. Jacobs et al. (10) concluded that the 30-s Wingate test was of too short a duration to quantify the glycolytic anaerobic capacity. Results of the present study support this conclusion as glycolysis still made a very significant contribution from the 30th s onward to the end of the 90-s test. The 90-s test can perhaps yield a more reliable estimate of the total glycolytic capacity, but a slightly longer test may also be contemplated to assess the total capacity of the glycolytic pathway. Development of such a test will undoubtedly encounter many difficulties such as pacing that occurs in a longer event and unwillingness of subjects to perform such demanding work in the laboratory. The results of the present study suggest that the 10-, 30-, and 90-s tests can be useful in assessing various aspects of the anaerobic capacity and power of athletes and nonathlete individuals alike. We conclude that these tests allow a valid approximation of (a) the capacity and power of the two anaerobic energy pathways and (b) the peak aerobic power.

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