The maximally accumulated oxygen deficit as an indicator of anaerobic capacity

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ABSTRACT

SCOTT, C. B., F. B. ROBY, T. G. LOHMAN, and J. C. BUNT. The maximally accumulated oxygen deficit as an indicator of anaerobic capacity. Med. Sci. Sports Exerc., Vol. 23, No. 5, pp. 618–624, 1991. Recently, a procedure has been established for the determination of the maximally accumulated oxygen deficit (MAOD) (Medbo et al., J. Appl. Physiol. 64:50–60, 1988) as an indicator of anaerobic capacity. We hypothesized that, if MAOD were a valid indicator of anaerobic capacity, it should distinguish between aerobically and anaerobically trained athletes and correlate with other existing anaerobic testing measures. Subjects were four distance and five middle distance runners, three sprinters, and four controls. The subjects ran for 2–3 min at 125–140% of VO_2max until exhaustion, and the accumulated O_2 deficit for that run was calculated by an extrapolation procedure. Subjects also performed the Wingate cycle ergometer test and runs of 300, 400, and 600 m. (Only athletes performed the runs.) Post-exercise blood lactates were obtained following the supramaximal treadmill run. MAOD (in O_2 equivalents—ml·kg^{-1}) was higher for the sprinters (78) and middle distance runners (74) than for the long distance runners (56) and control subjects (56) (P < 0.05), indicating a greater anaerobic capacity for the former two groups. Consequently, the relative anaerobic contribution was larger for the sprinters (39%) and middle distance runners (37%) than for the long distance runners (30%; P < 0.05). Significant correlations were found between MAOD and both Wingate power and treadmill work for all subjects and between Wingate power, Wingate capacity, treadmill work, and 300 m time for the athletes, suggesting that relationships do exist among MAOD and other anaerobic test measures. Potential use of MAOD as an indicator of anaerobic capacity is therefore promising and should be further explored.

SUPRAMAXIMAL, TRACK ATHLETES, ENERGY EXPENDITURE, WINGATE CYCLE ERGOMETER TEST, FIELD TEST RUNS

The maximum amount (i.e., quantity) of ATP which can be supplied by the anaerobic energy system has been termed anaerobic capacity (21). Direct attempts at anaerobic energy quantification from muscle biopsy samples can give us some clue as to anaerobic capacity determination through ATP-PC breakdown and muscle lactate concentrations, but the procedure is invasive, expensive, and provides information on relative concentrations, not amounts. Since the active muscle mass is not known, the anaerobic energy contribution can only be estimated, not measured. Currently, the most popular tests of anaerobic capacity involve the collection of a work score during short duration, high intensity activity. The validity of such tests rests on the premise that if the activity is intense enough and long enough in duration then the capacity of the anaerobic energy system has been reached. Unfortunately, this work score includes both an aerobic and an anaerobic energy component. Indeed, for the Wingate test, which is only 30 s in duration, as much as a 9–19% energy contribution from aerobic energy sources exists (17), depending on mechanical efficiency.

A true measure of anaerobic capacity would need to clearly separate and define anaerobic and aerobic energy production. The measure of maximally accumulated oxygen deficit (MAOD) has been proposed as a measure of anaerobic capacity (21). The MAOD relies on an extrapolation procedure using the linear work-load-oxygen uptake relationship based on several submaximal treadmill tests. From these data a regression line is drawn (representing running economy) so that supramaximal oxygen uptake (energy expenditure) can be predicted. MAOD is taken as the difference between the predicted supramaximal oxygen uptake and the actual oxygen uptake during a 2–3 min treadmill run to fatigue.

Previous research has demonstrated that MAOD remains unchanged under hypoxic conditions, revealing independence from aerobic energy sources (18,21). In addition, MAOD remains unchanged with high intensity exercise of 2–16 min in duration (16,21). That the MAOD reaches an maximal, unchanged value after supramaximal exercise supports the concept of a limited energy production by the anaerobic energy system (21). This MAOD "ceiling" further indicates that at least 2
min are needed to collect an anaerobic capacity measurement. Shorter duration tests may not stress the maximum capacity of the anaerobic energy system (14, 21, 22, 29, 32).

Since direct measurements of anaerobic capacity are lacking and thus no "gold standard" exists for direct validation, we proposed to test the validity of MAOD through indirect, applied means. We hypothesized that groups of sprint and distance trained athletes would reveal differences in anaerobic (as measured by MAOD) energy contributions during a 2–3 min supramaximal treadmill test. These differences would occur because of training and/or genetic factors. Correlations between MAOD and other popular anaerobic tests were also performed to determine the relationship MAOD has with these existing tests.

METHODS

Subjects. Twelve NCAA Division I varsity track athletes, along with four university students, volunteered for this study (Table 1). The athletes were well trained subjects who trained year-round for their respective events for indoor and outdoor competition. Subject consent forms approved by the University of Arizona Human Subjects Committee were signed by each participant. The athletes comprised three distinct groups of runners: 1) three sprinters (200–400 m), 2) five middle distance runners (800–1500 m), and 3) four distance runners (3000–10,000 m). The four control subjects were healthy college-aged males with no active participation in track and field athletics.

Energy expenditure determinations. Each subject underwent a minimum of five treadmill runs with concomitant oxygen uptake measurement. Oxygen uptake was obtained from an on-line, computerized metabolic system that incorporated a mixing chamber with Ametek gas analyzers, a Parkinson-Cowan C-D4 gas meter, and a Hans-Rudolph high velocity respiratory valve (#2700). Expired air was analyzed continuously and expressed in 30 s time periods. Maximal oxygen uptake (VO₂ max) was determined once for each subject using a protocol in which speed was held constant and grade was elevated 3% every 2 min until voluntary exhaustion. This protocol exhausted the subjects within 9–14 min. Supramaximal energy expenditure was determined using an extrapolation method adapted from procedure 3 of Medbo et al. (21). Briefly, three 10-min. submaximal tests were performed on separate days at a grade of 10.5% and at speeds which elicited oxygen uptakes of 85–100% of VO₂ max. The mean of the oxygen uptake values during the last 3 min of each submaximal test represented energy expenditure at each workload. From the three submaximal treadmill runs and a constant Y-intercept of 5.0 ml·kg⁻¹·min⁻¹ (representing standing metabolic energy expenditure), a linear relationship was established between treadmill speed and oxygen uptake. The oxygen demand for supramaximal exercise was determined by linear extrapolation from these three points and the Y-intercept. This relationship of treadmill speed and oxygen uptake is a measurement of running economy, and, due to the large individuality involved with this measurement for each subject, which can vary the slope of this line, the results must be expressed independently of each other. (These data cannot be pooled.) A minimum of one supramaximal treadmill test also was performed at a grade of 10.5% and a speed eliciting exhaustion within 2–3 min. The difference between the estimated oxygen demand and the measured oxygen uptake of the supramaximal treadmill run was integrated over the whole exercise period, and this difference, called the accumulated oxygen deficit, is used as a measure of the anaerobic energy release during the 2–3 min run (21). During the first 2 min of supramaximal exercise, this difference was calculated for each 30 s time period. Because the runners did not reach exhaustion at these precise 30 s intervals, the additional differences were calculated for each second between the last recorded VO₂ and the estimated oxygen demand. All subjects reached VO₂ max during the supramaximal run, and a plateau in oxygen uptake at VO₂ max was seen for all subjects at the 2 min mark. Aerobic energy expenditure and MAOD for the supramaximal run were calculated in oxygen equivalents (O₂ in ml·kg⁻¹). All treadmill tests were performed at least 2 d apart.

**Anaerobic power and capacity work tests.** Blood lactate samples were collected in 50 µl capillary tubes from a finger stick 5 min following the supramaximal treadmill run. Blood samples were then added to two drops of sodium fluoride and cetrimonium bromide to lyse the red blood cells. Analyses were done with a Yellow Springs Lactate Analyzer. Wingate tests were

<table>
<thead>
<tr>
<th>Group</th>
<th>Event</th>
<th>N</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>3000 m+</td>
<td>4</td>
<td>21.0 ± 2.1</td>
<td>181.4 ± 4.7</td>
<td>66.5 ± 4.2</td>
</tr>
<tr>
<td>MD</td>
<td>800–1500 m</td>
<td>5</td>
<td>21.5 ± 1.5</td>
<td>182.2 ± 6.6</td>
<td>69.5 ± 3.1</td>
</tr>
<tr>
<td>S</td>
<td>200–400 m</td>
<td>3</td>
<td>19.0 ± 1.0</td>
<td>180.3 ± 7.2</td>
<td>74.0 ± 8.9</td>
</tr>
<tr>
<td>C</td>
<td>—</td>
<td>4</td>
<td>24.3 ± 2.5</td>
<td>182.2 ± 6.5</td>
<td>82.6 ± 6.2</td>
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D = distance; MD = middle distance; S = sprinters; and C = controls.
performed on a modified Monark cycle ergometer. Four magnets were placed at 1/4 revolution intervals on the pedal crank and revolutions counted with a transducer positioned within 2 mm of the rotating magnets. An Apple II-E computer received the signal from the transducer, and total work was computed for each 5 s of the 30 s Wingate test. Subjects started pedaling at maximal velocity upon a verbal command, and, within 1–2 s of pedaling, a load was applied to the rotating flywheel which corresponded to 0.09 kg·kg⁻¹ of body weight. Anaerobic power was determined as the highest power attained during any 5 s interval and recorded as W·kg⁻¹ of body weight. Anaerobic capacity was measured as the total work during the 30 s time period and recorded in kJ. Each subject performed two Wingate tests, and the better score was recorded. Treadmill work was obtained during the supramaximal treadmill run and recorded in kg·m (work = body weight (kg) × treadmill speed (m·min⁻¹) × % grade × time (s)).

All athletes (control subjects did not participate) were given field test runs of 300, 400, and 600 m. These runs were performed over a 2 wk period of “time trials.” The athletes performed one trial at each distance in a true competitive fashion. The start of each event commenced with the firing of a starter’s pistol, and times were collected with a hand-held stopwatch.

Statistics. Statistical comparisons were computed using analysis of variance for repeated measures and Duncan’s multiple range procedures to determine significance among groups. Pearson product-moment correlations were used to determine the degree of association among MAOD and the other anaerobic performance tests (Wingate cycle ergometer work, treadmill work, blood lactate measurements, and field test run scores). Statistical significance was established at P ≤ 0.05. Values are expressed as means ± SD.

RESULTS

Group differences. Means, SD, and group differences are shown in Table 2. MAOD values (O₂ in ml·kg⁻¹) as an absolute measure of total anaerobic energy expenditure (anaerobic capacity) for distance runners, middle distance runners, sprints, and controls were 56 ± 5, 74 ± 7, 78 ± 3, and 56 ± 10, respectively. Significant differences were seen between distance and middle distance runners, distance runners and sprints, middle distance runners and controls, and sprinters and controls (P ≤ 0.05). The largest values were reported for sprinters and middle distance runners (Fig. 1). Consequently, the relative contribution from anaerobic sources ranged from 30 ± 2% for the long distance runners to 38 ± 3% for the sprinters and middle distance runners (P ≤ 0.05; Fig. 2). No significant differences among test subjects were seen with the other anaerobic work related tests. Group differences among athletes were only evident with the 300 m run times.

Correlations. Because the control subjects did not participate in the field test runs, two separate sets of correlations were performed. Correlations in Table 3 include all subjects; those in Table 4 are with the athletic groups alone (no control subjects). For all four groups of subjects, significant correlations were found between the MAOD and the Wingate 5 s power (W·kg⁻¹) (0.70, P ≤ 0.01) and treadmill work (kg·m) (0.66, P < 0.01).

![Figure 1—Absolute anaerobic and aerobic energy contributions (ml·kg⁻¹) are given for supramaximal treadmill exercise lasting 2–3 min. The anaerobic figures are maximally accumulated oxygen deficit (MAOD) values. Aerobic energy contributions should be viewed with caution as the duration of the run varied among subjects and this could affect the cumulative aerobic contribution. MAOD plateaus with exhausting exercise lasting 2 min or more and thus represents a true capacity value (see Discussion).](image-url)
A relationship also was seen between the Wingate 5 s power (W·kg⁻¹) and treadmill work (kg·m) (0.53, P ≤ 0.05). No correlations were found with blood lactate levels.

Correlations with the three athletic groups (Table 4) were seen among MAOD and Wingate 5 s power (W·kg⁻¹) (0.69, P ≤ 0.05), Wingate capacity (kJ) (0.64, P ≤ 0.05), treadmill work (kg·m) (−0.62, P ≤ 0.05) and 300 m run time (s) (−0.76, P ≤ 0.01). The 300 m run time among the groups of athletes also correlated well with the other indicators of anaerobic ability, which included Wingate capacity and 400 m run time, as well as treadmill work and blood lactate concentrations.

DISCUSSION

For prolonged activity, the quantification of energy expenditure is a relatively simple task involving measurement of oxygen uptake. During brief, intensive activity, no direct method exists for quantification of anaerobic energy contributions. With the use of MAOD, it is possible to obtain a measurement of energy expenditure separate from that produced aerobically (18,21). We hypothesized that MAOD, as a valid indicator of anaerobic capacity, would reveal differences among groups of aerobically and anaerobically oriented athletes and reveal correlations with other existing anaerobic ability measures. This was indeed evident for our study.

Among the athletes, MAOD was significantly higher among sprinters and middle distance runners than it was for distance runners, which suggests a greater anaerobic capacity for the former two groups. Previous research has shown that sprint type athletes possess a propensity toward a greater percentage of fast twitch, glycolytic fibers (4,7,29) and, presumably, a greater anaerobic capacity. However, increased fast twitch fiber percentages among these athletes are not always evident (9,20). In such cases, anaerobic capacity also may be enhanced by an increased muscle buffering ability (20,26), allowing the continuation of anaerobic glycolysis.

With relative energy expenditure values (Fig. 2), anaerobic energy contributions also were larger for sprinters and middle distance runners than for distance runners. Aerobic energy contributions were larger for the distance runners during the supramaximal treadmill run. However, time to fatigue varied among subjects during the 2–3 min period, so an accurate aerobic energy contribution during these runs cannot be obtained. Nevertheless, the relative energy contributions are similar to those devised by Gollnick and Hermansen (8) for this time frame. They state that a 60% aerobic

![Figure 2—Relative anaerobic and aerobic energy contributions are given for supramaximal treadmill exercise lasting 2–3 min. These energy contributions should be viewed with caution as the duration of the run varied among subjects and this could affect the cumulative aerobic contribution.](image)

| TABLE 3. Correlations between various anaerobic measures among sprinters, middle distance runners, distance runners, and control subjects (N = 16). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Q₀ deficit (ml·kg⁻¹) | Wingate Peak Power (W·kg⁻¹) | Wingate Capacity (kJ) | Treadmill Work (kg·m) | Lactate 5-min Post (mmol·l⁻¹) |
| Wingate peak power (W·kg⁻¹) | 0.70** | 0.45 | 0.44 | 0.22 | 0.15 |
| Wingate capacity (kJ) | 0.42 | 0.65* | 0.53* | 0.44 | 0.15 |
| Treadmill work (kg·m) | 0.65* | 0.53* | 0.44 | 0.22 | 0.15 |
| Lactate 5-min post (mmol·l⁻¹) | 0.44 | 0.22 | 0.15 | 0.15 | 0.15 |

* P ≤ 0.05; ** P ≤ 0.01.

| TABLE 4. Correlations between various anaerobic measures among distance runners, middle distance runners, and sprinters (N = 12). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Q₀ deficit (ml·kg⁻¹) | Wingate Peak Power (W·kg⁻¹) | Wingate Capacity (kJ) | Treadmill Work (kg·m) | Lactate 5-min Post (mmol·l⁻¹) | 300 m time (s) | 400 m time (s) | 600 m time (s) |
| Wingate peak power (W·kg⁻¹) | 0.69* | 0.72** | 0.71** | 0.25 | 0.15 | 0.15 | 0.15 |
| Wingate capacity (kJ) | 0.64* | 0.58* | 0.67** | 0.25 | 0.15 | 0.15 | 0.15 |
| Treadmill work (kg·m) | 0.62* | 0.58* | 0.67** | 0.25 | 0.15 | 0.15 | 0.15 |
| Lactate 5-min post (mmol·l⁻¹) | 0.67** | 0.58* | 0.67** | 0.25 | 0.15 | 0.15 | 0.15 |
| 300 m time (s) | −0.57 | −0.54 | −0.54 | 0.15 | 0.15 | 0.15 | 0.15 |
| 400 m time (s) | −0.57 | −0.54 | −0.54 | 0.15 | 0.15 | 0.15 | 0.15 |
| 600 m time (s) | −0.57 | −0.54 | −0.54 | 0.15 | 0.15 | 0.15 | 0.15 |

* P ≤ 0.05; ** P ≤ 0.01; *** P ≤ 0.001.
and 40% anaerobic contribution exists for activity of a 2 min duration, which would approximate the values found for sprinters and middle distance runners in our present study but would be misrepresentative of the values we found for distance runners. With our present data, the metabolic differences found among athletes with different training backgrounds must be emphasized. Medbo and Tabata (22) found a 65% aerobic and 35% anaerobic contribution with exercise lasting 2 min, which would approximate the values found for the control subjects in our current study.

The control subjects had a mean MAOD similar to distance runners although the standard deviation of this group was larger than for the athletes. It is quite possible that treadmill running experience could have produced a greater variation in the MAOD measurement among control subjects. This could explain some of the differences seen in the two separate sets of correlations. The high treadmill speed necessary for supramaximal testing may have resulted in underestimations in the running economy determinations for the control subjects which were not evident among the more experienced track athletes. Since the MAOD methodology relies heavily on the running economy measurement, any discrepancy could produce erroneous MAOD values. It is also possible that greater standard deviations were to be expected in the heterogenous group of control subjects, while the athletes who were divided into their specialty groups composed a more homogenous sample.

It is of interest to note that, when all four groups were compared, only the metabolic energy measures of maximal oxygen uptake and MAOD revealed significant group differences (Table 2). Close examination of the anaerobic work tests in Table 2 reveals a trend toward group differences, with the sprinters and middle distance runners having higher values than distance runners and controls. Perhaps the MAOD is a more sensitive indicator of anaerobic capacity, which is shown even with this small subject number. This may indicate some of the problems associated with anaerobic work-related tests. Although these work-related tests no doubt contain high degrees of anaerobic energy contributions, they also contain contributions from aerobic energy sources which have not been factored out. Other problems also exist. The Wingate test, for example, has been criticized due to widespread concerns of optimum loading of the flywheel (6,25,32), incomplete test duration for a true anaerobic capacity measurement (14,21,22,29,32), and a possible 9-19% aerobic energy contribution (depending on mechanical efficiency) during the 30 s anaerobic capacity test (17). Also of note is the similarity in treadmill work among distance runners and control subjects. Though distance runners ran faster than controls (4.5 vs 3.2 m s-1, P < 0.05), the controls averaged 16 kg heavier, which apparently evened out treadmill work among the two groups. Supramaximal run times were not different among groups.

Blood lactate measurements were not significantly different between groups. Correlations between the other anaerobic tests and blood lactates were limited. Trends also exist, however, for higher blood lactate levels in sprinters compared with distance athletes after maximal exercise, which were evident in this as well as other studies (10,23). While it is tempting to judge the extent of anaerobic metabolism from blood lactate levels, discrepancies in production and removal rates of lactate (3.5,11,12) can only support the conclusion that one cannot quantitatively determine the glycolytic contribution from such data.

Among field test runs, the 300 m times were able to distinguish among all three groups of athletes. Because correlations with the other anaerobic tests were high for this measure, the 300 m run shows promise as an indicator of anaerobic ability among runners. Thomson (31) has previously shown similar distances to correlate well with incremental changes in blood lactate values among athletes.

Correlations with MAOD and the other anaerobic work tests further support the validity of MAOD as an indicator of anaerobic capacity, suggesting that some commonalities of anaerobic ability exist among tests. Other studies also have revealed correlations between various anaerobic tests (13,19,24,28,30), and, though these correlations are not extremely high, they do reveal relationships and further attest to the difficulties associated with anaerobic testing. One such difficulty may be the involvement of separate motor skill tasks (task specificity) among the anaerobic tests, which may contaminate anaerobic relationships (2).

The MAOD also has some limitations. Supramaximal energy expenditure must be estimated for MAOD determination, and inaccurate submaximal running economy measurements which are used for the extrapolation procedure in estimating supramaximal energy expenditure and/or the possibility of lower running economy values above maximal VO2 levels (running economy may worsen during supramaximal runs) could produce drastic error (27). However, since MAOD remains unchanged with fatiguing exercise lasting 2-16 min (16,21), this suggests that a linearity of the supramaximal oxygen consumption-workload relationship does exist and that estimated energy expenditure may not be far from actual values. If the relationship deviated upward at exercise levels above VO2 max at metabolic extremes, MAOD would be smaller at the lower workloads (longer tests) and much larger at the heavier workloads (short tests). This is not seen. Energy contributions from stored oxygen located within hemoglobin and myoglobin also present concern. Stored oxygen contributions have been estimated to compose 10% of the total anaerobic energy expenditure (21,27).
The measurement of MAOD can be a difficult and time-consuming procedure. Although various methods are available to collect VO\textsubscript{2} data, a breath-by-breath system would provide better resolution of VO\textsubscript{2} kinetics at the start of exercise and perhaps provide interesting information on the time course of the VO\textsubscript{2} response among groups. In this study and the original investigation by Medbo et al. (21; see Fig. 1), oxygen uptake measurements were taken at 30 s intervals. Though due to this procedure some discrepancies in oxygen uptake may exist, both studies had subjects achieve oxygen uptake values during the supramaximal run similar to those seen on a separate maximal treadmill test and, in addition, plateaus were seen at VO\textsubscript{2max} during the exhaustive treadmill run. Moreover, Åstrand and Saltin (1) have clearly shown that exercise intensity has a great effect on oxygen uptake kinetics, and for this study the primary concern was the 2-3 min time to fatigue which resulted in differing running intensities among subjects and among groups. Thus, though the slopes of the VO\textsubscript{2} responses cannot be accurately calculated, the major concerns of oxygen uptake methodology have been met.

The MAOD has been suggested by several investigators as an anaerobic capacity measurement. MAOD shows potential as an anaerobic capacity measure because of its separation from aerobic energy sources (18,21) and its apparent leveling off or ceiling with fatiguing exercise lasting 2-16 min (16,21), indicating a limited anaerobic energy system. The oxygen deficit also has been found to have a linear relationship with phosphagen depletion and muscle lactate concentrations (15); however, muscle biopsy procedures have not been performed with the MAOD method. In addition, our study has shown that MAOD reveals differences among anaerobically and aerobically trained athletes and that correlations exist between MAOD and other aerobic work-related tests. The MAOD, therefore, shows promise as an indicator of anaerobic capacity measurement and should be further explored.

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