The Accumulated Oxygen Deficit Measure and Its Application in Pediatric Exercise Science

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A definitive measure for assessing the energy contribution of anaerobic pathways during exhaustive exercise remains inconclusive. The accumulated oxygen deficit (AOD) has been used in several studies to estimate energy contribution. The underlying assumptions of the AOD measure have been criticized for underestimating the true contribution of anaerobic metabolism in high intensity exercise. Indeed, the AOD measure has been the subject of much controversy. Several of the physiological exercise responses of children may lead to an even greater underestimation of the anaerobic energy contribution to high intensity exercise in children than adults when AOD measures are calculated.

In its purest definition, anaerobic capacity is the total amount of adenosine triphosphate (ATP) that can be resynthesized via anaerobic pathways in a single bout of high-intensity exercise (10, 13). To precisely estimate the quantity and capacity of anaerobically resynthesized ATP, invasive or expensive procedures (e.g., muscle biopsies or magnetic resonance imaging) are required. These procedures would be useful in detecting changes in pre- and postexercise concentrations of anaerobic-based muscle metabolites. Estimates of changes in these metabolites may be equated to the amount of ATP produced under predominantly anaerobic conditions. Spriet (26), however, cautioned that precision in even these procedures would be compromised by the associated assumptions concerning muscle lactate flux and oxidation, glucose uptake, the accumulation of glycolytic intermediates, and an acceptance of site-specific data as representative of a whole body response. Furthermore, these procedures are commonly beyond the ethical and financial constraints imposed on pediatric exercise scientists.

Most traditional tests for assessing anaerobic characteristics in pediatric populations have focused on power output under short-term, high-intensity conditions. Most of these tests have been criticized for not actually determining the capacity of the anaerobic system (24, 29). The purpose of this review is to discuss a relatively recent measure proposed for estimating the maximal amount of anaerobic energy released during high intensity exercise to exhaustion: the accumulated oxygen deficit (AOD).
Measuring the Accumulated Oxygen Deficit

The concept of oxygen deficit was first published by Krough and Lindhard (12). Hermansen and Medbø (11) revised the measure of estimating $\text{O}_2$ deficit in high-intensity conditions based on an individual’s responses to steady state submaximal exercise. In this measure, the work rate and its corresponding oxygen-cost data for each of several steady state tests of varying intensities were used to calculate a standard least squares linear regression: $y = a + bx$, where $y = \text{VO}_2$, and $x = \text{work rate}$. From this submaximal information, a “supramaximal” work rate was predicted from the known $\text{VO}_{\text{max}}$: $x = (y - a)/b$. A maximal aerobic power test is accepted as the upper limit, or a 100% representation of the aerobic energy system’s contribution to exercise. The contributions to the aerobic system beyond 100% are acknowledged as realistically impossible. Predicted $\text{VO}_2$ costs for supramaximal exercise were subsequently referred to as a “theoretical” estimation of a “purely aerobic” cost for a given supramaximal work rate. Thus, the least squares linear regression equation provides a work rate that would elicit the theoretical linear extrapolations for the prediction of aerobic costs for a given supramaximal intensity. The theoretical aerobic cost incurred over time is known as the “total accumulated $\text{O}_2$ demand.” The difference between the predicted total accumulated $\text{O}_2$ demand and the actual measured aerobic cost over the time is termed the accumulated oxygen deficit (AOD, Figure 1).

Measuring the Aerobic Contribution in AOD

One of the inherent difficulties in noninvasive estimates of anaerobically derived energy during high-intensity exercise to exhaustion is the finite depletion or capacity of the anaerobic energy pathways. This task becomes one of identifying the transitional point at which the dominance of anaerobic energy supply surpasses the contribution of ATP from aerobically driven pathways. Significant contribution from aerobic pathways can occur in high-intensity, exhaustive exercise that lasts longer than 60 to 90 s (26). Within the estimated total accumulated oxygen demand, measurements of the actual accumulated oxygen uptake enabled investigators to report the relative contributions of aerobic and anaerobic energy sources. This was calculated by dividing the measured $\text{O}_2$ costs by the amount of theoretical $\text{O}_2$ predicted for the exercise time to give the relative contribution from aerobic pathways. Thus, the remainder of the total accumulated $\text{O}_2$ demand was attributed to anaerobic energy sources. Using the outlined manipulations of the data, Medbø and Tabata (17) examined the relative importance of the aerobic and anaerobic energy release in supramaximal tests. They emphasized that there was a substantial contribution from aerobic energy sources even in exhaustive exercise bouts of a duration of 30 s. Aerobic energy contributions during cycling exercise to exhaustion for 30 s, 1 min, and 2 min have been reported to represent 40, 50, and 65% of the total energy released (17).

Therefore, Medbø (13) speculated that a 50-50 split in aerobic and anaerobic contributions to exercise occurred after 1 min of intense exercise. Similarly, Withers et al. (29) reported a 49% aerobic contribution after 60 s of work. Both of the aforementioned studies indicated that relative aerobic contribution increased with exercise duration, and conversely decreased with exercise intensity. Within three supramaximal workloads used to measure AOD in children, it was also demonstrated that the percentage of aerobic contribution to the total energy expenditure was significantly greater with increasing exercise time to exhaustion and de-
Sample calculation of the AOD from data collected on an 11-year-old male tested on a constant load cycle ergometer.

“Mike,” age 11.1 years, has a mass of 37.2 kg and his peak VO₂ was 2.01 l·min⁻¹

(1) Submaximal testing
Steady state values determined from the following workloads:

<table>
<thead>
<tr>
<th>Watts</th>
<th>VO₂ 1·min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.91</td>
</tr>
<tr>
<td>70</td>
<td>1.12</td>
</tr>
<tr>
<td>80</td>
<td>1.23</td>
</tr>
<tr>
<td>90</td>
<td>1.33</td>
</tr>
<tr>
<td>110</td>
<td>1.62</td>
</tr>
</tbody>
</table>

The linear regression equation \[ y = a + b(x) \] computed from the above data is:
\[ VO₂ (1 \cdot min^{-1}) = 0.306 + .0117 (Watts) \] which has a correlation coefficient \( r = .996 \)

(2) Supramaximal predictions
The oxygen uptake at 130% VO₂ peak is \( (2.01 \times 1.3) = 2.61 \) l·min⁻¹
From the linear regression the workload representing 130% VO₂ peak is calculated:
\[ 2.61 = 0.30 + .0115 (unknown Watt) \]
Watts = \( \frac{y-a}{b} \)
\[ = 197 \text{ Watts} \]

Sample of calculations for AOD
Mike’s time to exhaustion at 197 Watts = 57.43 s (i.e. 0.957 min)
Total predicted oxygen demand for the exercise time \( \Sigma = 2.49 \) (liters)

The actual (measured) \( O₂ \) consumption for the exercise time from Douglas bag data was 1.21 (1·min⁻¹) and for the exercise time \( = 1.21 (1 \cdot min^{-1}) \times .957 \) (min) \( = \Sigma 1.07 \) (liters)

\[ \text{AOD} = \text{Predicted } O₂ \text{ for the exercise time} - \text{Actual } O₂ \text{ for the exercise time} \]
\[ = 2.49 - 1.07 \text{ liters} \]
\[ = 1.42 \text{ liters (absolute value)} \]
\[ = 38.17 \text{ ml·kg}^{-1} \text{ (relative value)} \]

Figure 1 — Sample calculation of an AOD measure.

creased with exercise intensity (Figure 2). For example, in tests averaging 47 and 123 s of work, the aerobic contributions were 40.8 and 61.6%, respectively.

Measuring the Anaerobic Contribution in AOD

In contrast to the predictable dynamics of the aerobic energy contribution under supramaximal exercise conditions, the relative contribution of anaerobic energy may demonstrate a plateau. The presence of a plateau has been accepted as representing an anaerobic capacity (13). The measure of anaerobic capacity, again by definition, is independent of the rate of exercise or the amount of time taken to exhaustion during a test. For example, a work rate eliciting exhaustion within 60 s will produce the same anaerobic energy release as a test to exhaustion performed at a lower intensity but lasting 2 min. Figure 2 presents AOD values obtained from prepubertal males and females during three supramaximal (110, 130, and 150% of VO₂ peak) exercise chal-
Figure 2 — Partitioning of accumulated oxygen demand (liters) into accumulated oxygen uptake and accumulated oxygen deficit of (i) boys and (ii) girls.

Challenges to exhaustion. Results from the young males in this study generally supported the concept that a plateau in the anaerobic energy contribution occurred with increasing intensity.

Underlying Assumptions of the AOD Measure

According to Medbø et al. (16), three assumptions underlie the accuracy of AOD as a measure of anaerobic energy released during exercise. The first states that an anaerobic energy contribution can be derived by subtracting the measurable aerobic energy costs from the total energy released. The second assumption states that
the relationship between work rate and $O_2$ is linear. The final assumption dictates that the ATP requirement is constant for a fixed exercise supramaximal intensity from the start to the end of the exercise bout. In addition to a lack of clarification of the procedures involved in AOD measures, these underlying assumptions have initiated substantial scientific debate in recent years.

**Controversies in the AOD Measure**

The underlying assumptions and procedures of the AOD measure remain controversial. Several authors have discussed difficulty in accepting that AOD can be used to quantify whole-body anaerobic energy turnover; however, each has acknowledged that this is the most accurate estimate available to date (3, 7, 9, 10). Recently, Jens Bangsbo and Jon Medbø (3, 14) published a debate of AOD as an accurate measure of anaerobic energy release. Given that the original estimates of energy release were calculated from muscle biopsy research, Bangsbo (3) believed the method appeared to be more valid for specific muscle groups than as an estimate of whole body anaerobic energy turnover. He was critical of the failure to account for the anaerobic contribution to submaximal exercise in the initial phases of testing. Medbø (14), in turn, argued that the overall effect of the results of submaximal anaerobic energy on the oxygen deficit turnover would be minimal. A further criticism of the AOD measure was described by Saltin (23), who reported that the lowest mechanical efficiencies were found at the highest relative intensities. Saltin et al. (25) reported 16–19% efficiency instead of 20–25% efficiency from subjects cycling close to maximal effort intensities. Reviewers of the AOD measure have consistently noted that estimations of the energy demand during intense exercise may not take into account additional sources of oxygen demand that might be exhibited at higher exercise intensities. These sources include the energy demands from the cardiorespiratory system responding to the added work of stabilizing muscle of the upper body under highly intense conditions, catecholamine activity, and the thermoregulatory mechanisms adjusting to increased demands from a rise in muscle temperature. Thus, the AOD measure has been criticized for underestimating the true oxygen demand (2, 3, 7, 10, 23, 24).

Reviewers of this measure have also been critical of the lack of detail provided in the description of submaximal procedures essential for the precision of the AOD measure (3, 10). Further research and clarification has been sought regarding the nature of protocols employed in the initial stages of submaximal testing such as: the appropriate number of tests, the reliability of the testing over time, the mixture of high and low intensities that are required to determine the work rate–$O_2$ relationship, the pedal frequency for cycling, and the slope of the treadmill for running during the submaximal tests. Each of these factors has been linked with substantial alterations in the work rate–$O_2$ relationship and the resultant AOD measures. Medbø believed that the precision of the method was enhanced by efforts made to inform, motivate, and familiarize subjects about the protocol, and highlighted the need for large numbers of 8- to 10-min steady-state submaximal tests, as well as routine and frequent equipment calibration (14).

**Application of AOD**

One of the most powerful challenges to the AOD measure has been to its ability to find an application within an athletic context. Green and Dawson (10) cited the
AOD measure as a poor correlate of running performances between 400-m and 1500-m distances. Bangsbo (3) believed that the value of the AOD measure in athletic populations may lie in intra-individual comparisons of anaerobic characteristics. He believed that if precisely the same testing protocol is used with athletes, then changes to anaerobic performance may be detected through the AOD measure. Bangsbo (3) dismissed the validity of cross-study comparisons because of inconsistencies with procedures used to estimate the relationship between oxygen uptake and submaximal exercise intensities in the increasing number of studies where AOD measures have been reported. Within the same studies, however, the AOD measure has been used to identify differences among groups of untrained, endurance-trained, and sprint-trained athletes (8). AOD differences in male and female adolescent athletes from the same anaerobic-based sport have also been reported (21). The AOD measure was further reported to be sensitive to changes following 6 weeks of anaerobic training in adult males and females (15).

AOD in Children

Limited data exist of AOD measures in pediatric populations. As previously mentioned, Bangsbo (3) argued that cross-study comparisons must be interpreted with caution when different exercise modes and populations are used. Testing in children has involved the use of constant load and isokinetic cycle ergometers, and treadmill running (5, 6, 19). The results demonstrate similar AOD values in the preadolescent males and females (5). AOD measures used in preadolescent males with exercise-induced asthma (EIA) were not different from those produced by a group of well-matched males without EIA (4). Perhaps the active nature set in the selection criteria for both groups of males in the study by Buttifant et al. (4) may help explain the comparable development of anaerobic characteristics. In preadolescent subjects exercising on isokinetic cycle ergometers, males produced more reliable AOD measures than did females (intraclass correlations of $R = .95$ and .87, respectively [18]).

Although limited, one study has measured AOD in a group of males from pre-, mid-, and postpubertal stages of development (28). The results demonstrated increasing AOD values that somewhat reflected the age and maturational increases through puberty. The increase in AOD through the various stages of puberty, however, was not linear. Therefore, it may be suggested that factors other than developmental stage or age may influence anaerobic performance. Perhaps anaerobic performances are a result of the advantages of exercise training and the resultant training status during pubertal years, particularly in adolescent males (20).

Using the AOD Measure With Children

The controversies surrounding the assumptions and procedures of the AOD measures become even more complex when children are subjected to this measure. Obtaining the greatest number of steady-state values at submaximal work rates becomes a challenge of avoiding steady state tests that do not induce oxygen drift at relatively high exercise intensities, and conversely, obtaining true $O_2$ costs from relatively low intensities where additional energy costs for balance and coordination need to be avoided. These tasks are perhaps more problematic in children than in adults, because the absolute submaximal work rate range is smaller in children.
than in adults. Furthermore, the request from Medbo (14) for the greatest possible number of submaximal tests in these formative procedures of the AOD measure does not compliment the desire for time-efficient testing procedures with pediatric populations. Children may, however, have an advantage in sustaining relatively higher intensity steady-state VO$_2$ values than adults (1).

There is also some evidence to suggest that children have an increased tendency to move from anaerobic to aerobic conditions rather rapidly. The findings of Poage et al. (22) and Springer et al. (27) implied that factors such as increased sensitivity to hypoxic conditions, and less storage capacity for CO$_2$ could lead to adaptations in the child’s oxygen kinetics that mask a true indication of the capacity of the anaerobic power at the onset of exercise. If children are highly sensitive to hypoxic conditions such as those occurring at the onset of very intense exercise, then assumptions about constant efficiency from extrapolations for supramaximal conditions may not be as valid in child-based populations as those in adults. If this is the case, then underestimations in predictions of accumulated oxygen demand may be even greater in children than in adults. It appears that even if all the adult-based controversies surrounding this measure were resolved, questions would remain concerning the validity of supramaximal oxygen demands being predicted from submaximal performances within pediatric populations.

**Conclusion**

With a consolidation of the validity of the AOD measure in pediatric populations, testing could be extended to research into the applied fields of exercise prescription and enhanced performance. The noninvasive, challenging nature of the AOD measure for determining additional anaerobic characteristics in subjects makes it a potentially viable protocol for use with children. To date, as previously stated, AOD remains the most accurate estimate of anaerobic energy release under high intensity exercise stresses.

**References**