Determining Anaerobic Capacity in Sporting Activities

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Anaerobic capacity/anaerobically attributable power is an important parameter for athletic performance, not only for short high-intensity activities but also for breakaway efforts and end spurs during endurance events. Unlike aerobic capacity, anaerobic capacity cannot be easily quantified. The 3 most commonly used methodologies to quantify anaerobic capacity are the maximal accumulated oxygen deficit method, the critical power concept, and the gross efficiency method. This review describes these methods, evaluates if they result in similar estimates of anaerobic capacity, and highlights how anaerobic capacity is used during sporting activities. All 3 methods have their own strengths and weaknesses and result in more or less similar estimates of anaerobic capacity but cannot be used interchangeably. The method of choice depends on the research question or practical goal.

Keywords: MAOD, critical power, efficiency, modeling, exercise performance

Measuring Anaerobic Capacity/Anaerobically Attributable Power

There are several methods available to estimate anaerobic capacity during various types of sports. The most frequently used method is the maximal accumulated oxygen deficit (MAOD). Medbø et al. showed that the O₂ deficit, a concept introduced by Krogh and Lindhard, reached maximal values when accumulated over an exercise bout of at least 2 minutes, from which they concluded that the MAOD is representative of anaerobic capacity. Another method that has been used in the literature to quantify...
anaerobic capacity is the critical power (CP) concept, introduced by Monod and Scherrer.\textsuperscript{7} The $W'$, one of the parameters of the CP concept, is originally thought to represent anaerobic capacity or anaerobic work capacity.\textsuperscript{14–16} The third and final method that will be discussed in this review is the gross efficiency (GE) method,\textsuperscript{17} which is based on the methodology first described by Serresse et al.\textsuperscript{8} These 3 methods used to determine anaerobic capacity or anaerobically attributable power will be briefly discussed.

**MAOD Method**

The MAOD method is based on an individual linear relationship between treadmill speed or power output (PO) and VO$_2$.\textsuperscript{6,18,19} Extrapolation of this relationship to supramaximal exercise intensities provides the VO$_2$ demand corresponding to a certain supramaximal workload (Figure 1A). The duration of the supramaximal exercise bout (~2–3 min) times the predicted VO$_2$ demand results in the accumulated VO$_2$ demand. The MAOD can be calculated by subtracting the VO$_2$ uptake measured during and integrated over the duration of the supramaximal exercise bout (ie, the accumulated VO$_2$ uptake) from the accumulated VO$_2$ demand (Figure 1A).\textsuperscript{6}

Recently, a more comprehensive review of the MAOD method was published.\textsuperscript{2} That review addresses the effect of the number and duration of submaximal exercise bouts necessary for the construction of the PO–VO$_2$ relationship and of different supramaximal exercise bouts necessary for the construction of the PO–VO$_2$ relationship. In addition, a supramaximal exercise protocol and exercise modality that is most specific to the athlete’s event or sport should be chosen.

**CP Concept**

Originally developed by Monod and Scherrer,\textsuperscript{7} the CP concept has been used to differentiate between aerobic and anaerobic exercise. Equation 1 describes this CP concept:

$$ PO = \frac{W'}{t} + CP $$  \hspace{1cm} (Eq 1)

in which $t$ is the time to exhaustion at a certain PO (Figure 1B). The parameters of the CP concept can be determined by having subjects perform 4 or more constant PO tests to exhaustion. Preferably, these tests are conducted on multiple days, and the chosen POs range of ~75% to 105% of the maximum PO attained during a maximal incremental exercise test.\textsuperscript{20} An alternative way to estimate $W'$ and CP is to perform 4 or more time trials of different length and measure average PO and performance time.\textsuperscript{21}

Monod and Scherrer initially defined the CP of a muscle or muscle group as the maximum rate it can maintain for a very long time without fatigue.\textsuperscript{7} In modern times, the CP is best understood as a threshold phenomenon, defining the boundary between the heavy and severe exercise-intensity domains.\textsuperscript{22–27} It represents the highest work rate that can be sustained while maintaining a physiological steady state and appears to occur at a work rate close to the maximal lactate steady state.\textsuperscript{25,28}

Exercise above the CP results in an inexorable rise in VO$_2$ (in the face of a constant external work rate) until VO$_2$\textsubscript{max} is attained and exhaustion ensues.\textsuperscript{22,24,25,29} This combination of factors has led to sub-CP exercise being referred to as aerobic.

The work capacity above CP is fixed; that is, the $W'$ (power–time integral > CP) remains constant regardless of the rate of its discharge. Originally, it had been thought that $W'$ consists of the energy produced through phosphocreatine hydrolysis, anaerobic glycolysis, and a small aerobic contribution from O$_2$ stores in the body.\textsuperscript{14–16} This led to a popular understanding of $W'$ as anaerobic work capacity. The construct itself appears robust, as the depletion and reconstitution of $W'$ can be calculated with some precision under a variety of circumstances.\textsuperscript{12,30–32} These observations suggest that the power–time relationship is a highly organized physiological process. However, it has proven difficult to ascribe the $W'$ to any discrete variable.\textsuperscript{25,31,33}

**GE Method**

The GE method is based on calculating the aerobically attributable mechanical power ($P_{\text{ar}}$) and subtracting $P_{\text{ar}}$ from the total PO produced, which results in the anaerobically attributable mechanical power ($P_{\text{aer}}$; Figure 1C).\textsuperscript{8} Integrating $P_{\text{aer}}$ over time provides a measure of a subject’s anaerobic capacity. $P_{\text{aer}}$ can be determined from metabolic power input (PI) and the efficiency with which metabolic power is converted to mechanical power. To determine GE, a subject needs to perform steady-state submaximal exercise,\textsuperscript{34} during which GE can be determined before the start of the supramaximal exercise bout. GE can be defined as the ratio between the mechanical PO and PI, in which PI can be calculated from VO$_2$ (expressed in L/s) and the oxygen equivalent (Equation 2).\textsuperscript{35,36}

$$ PI = VO_2 \times (4940 \times RER \times 16,040) $$  \hspace{1cm} (Eq 2)

where RER = respiratory exchange ratio. Anaerobically attributable power can be estimated for different high-intensity exercise bouts (ie, time trials\textsuperscript{4,11} and/or constant PO bouts\textsuperscript{17}), as long as PO, VO$_2$, RER, and GE are known.

**Are They the Same?**

There are several studies that have compared 2 of the 3 methods just described in determining anaerobic capacity/anaerobically attributable power.\textsuperscript{16,17,37} When comparing these methods, it has to be taken into account that the results of the MAOD method are expressed in terms of O$_2$ equivalents and that the results of the CP concept and GE method are usually expressed in mechanical units (joules or watts).
Figure 1 — Graphic representation of the different methodologies to determine anaerobic capacity/anaerobic attributable power (shaded area). (A) The maximal accumulated oxygen deficit method (adapted from Noordhof et al\textsuperscript{17}). (B) The critical power concept (adapted from Vanhatalo et al.\textsuperscript{20}). (C) The gross efficiency method (adapted from Noordhof et al\textsuperscript{17}).
Anaerobic capacity determined with the CP concept has been compared with anaerobic capacity estimated with the MAOD method, by Hill and Smith. They found no significant difference in anaerobic capacity between the 2 methods. Besides, the 2 anaerobic-capacity estimates were significantly correlated \( r = .77 \), from which they concluded that \( W' \) is a valid method to determine anaerobic capacity. In that study, anaerobic capacity estimated with the MAOD method was used as criterion measure. However, the exact methodology used to determine the MAOD has not been reported, which makes it difficult to interpret the findings of the study.

Bosquet et al determined anaerobic capacity during treadmill running using the MAOD method and the CP concept. The individual velocity–VO\(_2\) relationship, necessary to determine anaerobic capacity with the MAOD method, was based on the data of a maximal incremental exercise test performed on a treadmill. The initial velocity was set at 2.8 m/s, and velocity increased by 0.28 m/s every 2 minutes, from which it can be concluded that the velocity–VO\(_2\) relationship was not based on steady-state VO\(_2\) measurements, which makes the results of this study questionable. \( W' \) or anaerobic running capacity (ARC expressed in m or in mL O\(_2\) equivalents per kg) in the study of Bosquet et al was determined using 4 different models: a nonlinear 2-parameter model, 2 linear 2-parameter models, and a 3-parameter model. The 3-parameter model resulted in an average ARC that was about twice as high as the average ARC derived with the 3 other models. However, the ARC derived with this 3-parameter model and the 2 linear 2-parameter models was significantly correlated with the O\(_2\) deficit \( r = .57, r = .50, \) and \( r = .49 \), respectively). Bosquet et al concluded that although the definitions of the O\(_2\) deficit (or MAOD) and the ARC (or \( W' \)) suggest that both methods can be used to determine anaerobic capacity, they should not be used interchangeably.

Another study that compared anaerobic capacity obtained with the MAOD method and the CP concept was the study Zagatto and Gabotto. Hill and Smith made use of cycling exercise. Bosquet et al studied a group of middle- and long-distance runners on the treadmill, and Zagatto and Gabotto determined anaerobic capacity using both methods during a table-tennis-specific test. The constant-intensity submaximal exercise bouts necessary for the construction of the PO–VO\(_2\) relationship were table tennis sessions of 7 minutes in duration, during which balls were thrown at a certain constant frequency. Thus, a frequency–VO\(_2\) relationship was established. The individual linear relationship was based on 4 exercise bouts and a fixed y-intercept, determined as the baseline VO\(_2\) measured during a 10-minute rest period. The CP was in this case a critical frequency of balls thrown to the table tennis player. \( W' \) was estimated using 3 different mathematical equations (2 linear and 1 nonlinear), but none of the \( W' \) values were significantly correlated with the MAOD. Zagatto and Gabotto concluded that \( W' \) does not result in a valid estimate of anaerobic capacity during a table-tennis-specific test.

Based on the results of the studies comparing the anaerobic capacity estimated with the MAOD method and CP concept, it must be concluded that neither method results in significantly different estimates of anaerobic capacity. However, clear individual differences exist between the 2 methods, so it is advised to select 1 method and use that method consistently.

Noordhof et al compared anaerobic capacity calculated with 3 different MAOD procedures and the GE method. No significant differences in anaerobic capacity were found between the different methods. However, assessing the precision of these different methodologies resulted in significantly different 95% confidence intervals. The original MAOD method makes use of at least 10 submaximal exercise bouts with a duration of 10 minutes to establish the linear PO–VO\(_2\) relationship. However, in the literature this original methodology has been adapted in different ways; for example, shorter exercise bouts have been suggested, as well as the inclusion of a fixed y-intercept. Therefore, 3 different PO–VO\(_2\) relationships were established in the study of Noordhof et al: 1 based on the average VO\(_2\) from minutes 8 to 10 of 10 submaximal exercise bouts, without the inclusion of a fixed y-intercept, and 2 regression lines based on the average VO\(_2\) during minute 4, without (4-Y) and with the inclusion of a fixed y-intercept (4+Y). The results showed that the 4+Y MAOD procedure and the GE method resulted in smaller 95% confidence intervals, from which it was concluded that the 4+Y MAOD procedure or GE method should be used to determine anaerobic capacity. Clear individual differences in anaerobic capacity were found between the 2 methods, so it was advised not to use the methods interchangeably.

Unfortunately, there are no published studies available that compared the CP concept and the GE method in determining anaerobic capacity. Comparing these 3 different methodologies to determine anaerobic capacity/anaerobic attributable power gives us insight into the relationship between these different measurements. However, it remains uncertain if these indirect measurements are really valid and which measurement provides us the “real” anaerobic capacity, as direct measurements of anaerobic capacity during whole-body exercise are thus far not available.

The main conclusion that has to be drawn from the presented studies is that these 3 methods result in more or less similar estimates of anaerobic capacity when studied during running and cycling exercise. However, the MAOD method, CP concept, and GE method cannot be used interchangeably, as large differences can exist between these methods. When using the MAOD method, we advise to use 10 × 4-minute submaximal exercise bouts at intensities between 30% and 90% VO\(_{\text{max}}\), and to include a fixed y-intercept in the PO–VO\(_2\) relationship. When using the CP concept to determine anaerobic capacity, the 2-parameter model seems to result in a more valid estimate of anaerobic capacity than the 3-parameter model. The GE method is less time-consuming, but GE needs to be estimated at
the highest possible steady-state exercise intensity with an RER ≤ 1.0. Taking this into account, it seems to be possible to get a reliable estimate of anaerobic capacity during high-intensity exercise.

How Is Anaerobic Capacity Used During Sporting Activities?

It is evident that to perform optimally in short-duration activities, most of the anaerobic capacity needs to be used. During these short-duration activities, a strategy with an all-out anaerobic contribution to PO is often adopted.\textsuperscript{42} In contrast, middle- and long-distance events are characterized by a high anaerobic contribution at the beginning of the event and during the end spurt,\textsuperscript{4,11} without much anaerobic contribution during the middle section of the event. Although ultraendurance activities (eg, marathon running, multistage cycling events like the Tour de France) are often not associated with a high anaerobic energy contribution, surges during the race and end-spurt activities rely predominantly on the anaerobic system.\textsuperscript{43,44}

Is the W' Actually Fixed?
Can It Be Restored During Exercise?

In recent years, some light has been shed on processes that may contribute to the W'. For example, the slow component of pulmonary O\textsubscript{2} uptake in the severe domain appears to be related to the W' during constant-work-rate, all-out, and intermittent exercise.\textsuperscript{12,22,33,45,46} Similarly, studies using \textsuperscript{31}P magnetic resonance spectroscopy indicated that the complete depletion of the W' is associated with a consistently low phosphocreatine concentration and pH.\textsuperscript{47} Although an intrinsic relationship between the W' and VO\textsubscript{2} kinetics would clearly conflict with an "anaerobic" interpretation of the W',\textsuperscript{7,15} a recent investigation indicates that hypoxia both increases the CP and reduces the W'.\textsuperscript{52} This suggests that the CP and W' are interrelated and that the basic conceptual framework of the W' should be reconsidered.\textsuperscript{22,25,27}

Although we may be unable to consider the W' to be a strictly anaerobic parameter, it does indeed appear to represent a fixed work capacity if evaluated under consistent experimental conditions (ie, without glycolgen depletion\textsuperscript{15} or changes in oxygen tension\textsuperscript{27}). For example, the W' appears to be robust to manipulations of work rate within the severe domain, encompassing constant-work-rate, all-out sprint, ramp, and self-paced exercise.\textsuperscript{48} Since depletion of the W' results in exhaustion, or at least the inability to maintain a supra-CP work rate, it is important to understand whether the W' can be recovered during exercise, as many sports involve periods of time spent surging above the CP and periods of relative recovery (ie, time spent drafting while skating or cycling).

Fortunately, several authors have sought to apply the CP/W' paradigm to intermittent exercise, albeit with varying degrees of success.\textsuperscript{12,30,32,49,50} Morton and Billat\textsuperscript{32} published the first formal model that attempted to mathematically codify the depletion and reconstitution of the W' during intermittent exercise:

\[
t = n(t_u + t_r) + W' + \frac{n[(P_w - CP)t_u - (CP - P_t)t_r]}{P_w} - CP
\]

(Eq 3)

where \( t \) = total endurance time, \( P_w \) and \( P_t \) are equal to the work- and rest-interval power, and \( t_u \) and \( t_r \) are equal to the work- and rest-interval time. In this model it is assumed that the W' is depleted at a rate of \((P_w - CP)/s\) and recovered at a rate of \((CP - P_t)/s\).

The model described by Equation 3 was recently applied to intermittent cycling exercise by Chidnok et al\textsuperscript{46} to good effect, clearly demonstrating W' recovery. However, the model assumes linear kinetics of W' discharge and recharge, which conflicts with recent observations indicating that the W' is actually reconstituted curvilinearly.\textsuperscript{49} This is an important practical distinction, indicating that while a substantial portion of the W' can be recovered quickly, complete recovery may take 20 minutes or more.

Based in part on these data, Skiba et al\textsuperscript{12} recently developed a novel integrating function (W'\textsubscript{t}) that successfully accounts for the curvilinear depletion and reconstitution kinetics of the W' during intermittent exercise:

\[
W'_{bal} = W' - \int_0^t W'_{exp} \cdot e^{-(t-u)\tau_w} \quad \text{(Eq 4)}
\]

In Equation 4, W'\textsubscript{exp} is representative of the amount of the starting W' that is presently expended, while \((t-u)\) is equal to the time in seconds separating the portions of the exercise session where W' was used. The \( \tau_w \) is the time constant of the reconstitution of the W'—the time required to recover approximately 60% of the W'\textsubscript{exp}. Thus, the W'\textsubscript{bal} is representative of the difference between the measured resting W' and integral of the joules of the W' expended before time \( t \) in a training bout or race, which begins to be recharged exponentially any time PO falls below the CP.\textsuperscript{12}

The \( \tau_w \) appears to vary exponentially as a function of the difference (D\textsubscript{CP}) between recovery PO and the CP (Equation 5)\textsuperscript{12}.

\[
\tau_w = 546 \cdot e^{-(0.1D_{CP})} + 316 \quad \text{(Eq 5)}
\]

In other words, the closer the athlete approaches CP, the more slowly the outstanding W'\textsubscript{bal} is recovered. It may be helpful to visualize the implications of this relationship in terms of macroscopic phenomena. The relationship described by Equation 5 is precisely what would be observed where W' is representative of a vessel of water that could be emptied by a drain of variable size (ie, depending on how far above CP exercise occurs) and refilled by a tap with an adjustable flow (where the maximum flow rate is representative of CP). The level of water in the vessel is the remaining part of W' during the event.
GE During Supramaximal Exercise

Aside from the fact that GE is one of the most important factors determining performance, knowledge about GE is crucial for an accurate application of the described methods used to estimate the anaerobic capacity. All 3 methods assume a constant efficiency during the event. The MAOD method assumes a constant efficiency by using a linear relationship between PO or treadmill speed and VO2, the CP concept assumes a constant efficiency across the whole power and time domain,25 and the GE method uses GE values determined during warm-up exercise, assumes that GE determined during submaximal exercise is equal to GE during maximal exercise, and assumes that GE remains constant during the supramaximal exercise bout. Recent studies have shown that GE increases curvilinearly with increasing exercise intensity34,51 and decreases during submaximal52 and supramaximal exercise.3 The curvilinear increase of GE with increasing PO has its origin in the smaller relative contribution of maintenance metabolism in PI when intensity increases. When GE is determined at an intensity significantly lower than ventilatory threshold, GE will be underestimated and, thus, anaerobic capacity overestimated. The decrease in GE during prolonged submaximal and supramaximal exercise is associated with fatigue and appears to depend on the length and intensity of the exercise.53 Ignoring this decrease will result in underestimation of anaerobic capacity. Thus, it is very important to determine GE at the highest possible exercise intensity and to gain knowledge about the decrease in GE during exercise.

Given the preceding, it is difficult to precisely determine the effects of stochastic exercise on GE. De Koning et al34 have attempted to systematically evaluate the effect of different variables on the determination of GE. GE does appear to increase curvilinearly with increasing PO, but this effect decreases beyond ventilatory threshold.34 When GE is estimated during graded exercise it also appears that the length of the exercise stages is extremely important; GE is significantly overestimated during 1-minute exercise stages compared with GE measured during 3- or 6-minute stages.34 These findings are important, particularly in competitive sport, where work duration and PO cannot be controlled. Moreover, there is substantial evidence that recovery duration affects efficiency.34,55 The recently introduced approach to estimate GE during high-intensity exercise3 is highly relevant for refining the accuracy of the results provided by the GE method, because with this method the decline in GE can be estimated and the assumption that GE is a constant entity can be abandoned. With estimated decline in GE during the event, the calculated contribution of Pan to PO will be larger.

Ecological Validity

A major shortcoming of most methods of determining anaerobic capacity is that the exercise protocols used differ dramatically from competitive situations. Time-to-exhaustion tests are fundamentally different from time-trial exercise and bunch-type racing. Exercise protocols in which PO can vary spontaneously, as seen in competition, have higher ecological validity. The recent applications of the CP concept to stochastic exercise by Skiba et al12 and Chidnok et al48 are promising in this respect. An advantage of the GE method and the application of the CP concept by Skiba et al12 and Chidnok et al48 is that one obtains not only a measure for anaerobic work (integral of Pan or W′, respectively) but also information about the distribution of anaerobic work over time. Information about the distribution of anaerobic work can be of help for further understanding pacing strategies4,11 and the development of fatigue during competition.

Practical Applications and Conclusion

The 3 methods described and evaluated in this review all have their strengths and weaknesses; therefore, the method of choice depends on the research question or practical goal. The MAOD and W′ are capacity values that do not provide information about the distribution of anaerobic energy during exercise. The GE method, on the other hand, includes information about the distribution of anaerobic energy, which can be valuable in understanding pacing. In addition, the GE method is the only method that takes into account the decrease in efficiency during prolonged submaximal or supramaximal exercise. Recent applications of the CP concept are promising in making it possible to accurately model the discharge and recovery of W′ for both prescribed intermittent exercise and field data.

In conclusion, when monitoring athletes’ anaerobic capacity, the MAOD or GE method is preferred, as W′ is not a completely anaerobic measure. Questions about the discharge and recovery of a mostly anaerobic amount of work can best be studied with the CP concept. Finally, to increase knowledge about pacing, we suggest use of the GE method.

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