Estimation of accumulated oxygen deficit from accumulated blood lactate concentration during supramaximal running in middle-distance runners

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Abstract The maximal accumulated oxygen deficit (MAOD), which is the gold standard for anaerobic energy metabolism capacity, requires multiple tests for evaluation that impose a heavy load on subjects. The maximal accumulated blood lactate (ΔbLa) concentration is also a measure of anaerobic energy metabolism capacity, and is related to the accumulated oxygen deficit (AOD). Thus, AOD has been estimated by using ΔbLa (3.0 mL O\textsubscript{2} · kg\textsuperscript{-1} · mM\textsuperscript{-1}), but it is unclear if this coefficient is suitable for measurement of supramaximal running of athletes. The purpose of this study was to clarify the estimated expression of AOD by using ΔbLa from the relationship between MAOD and ΔbLa during supramaximal running in middle-distance runners. Eleven male middle-distance runners (800m running velocity: 425.3 ± 7.3 m·min\textsuperscript{-1}) took part in this study. They performed three running tests (maximal, submaximal and supramaximal running test) to evaluate MAOD and ΔbLa. MAOD and ΔbLa were 56.6 ± 6.0 mL O\textsubscript{2} · kg\textsuperscript{-1} and 9.9 ± 1.1 mM, respectively. We observed a significant positive relationship between MAOD and ΔbLa ($r = 0.73$); the regression line equation was $y = 3.58x + 18.6$. Results showed that the AOD per mM of the ΔbLa of athletes was 3.58 mL O\textsubscript{2} · kg\textsuperscript{-1}, which was 19% higher than the conventional coefficient value.

Keywords: athletes, anaerobic energy metabolism, lactic acid, oxygen

Introduction

The maximal amount of adenosine triphosphate (ATP) that can be resynthesized from the breakdown of phosphocreatine (ATP-CP system) and intramuscular glycogen by muscle and blood lactate accumulation (glycogenesis) is defined as the anaerobic energy metabolism capacity. The gold standard of anaerobic energy metabolism capacity is the maximal accumulated oxygen deficit (MAOD). However, multiple tests, such as submaximal and supramaximal exercise tests, are required to evaluate MAOD, which imposes a heavy load on subjects. The maximal accumulated blood lactate concentration is also known as a measure of anaerobic energy metabolism capacity. di Prampero & Ferretti observed a relationship between accumulated blood lactate concentration (ΔbLa) and accumulated oxygen deficit (AOD), and demonstrated that AOD could be estimated from ΔbLa; the coefficient for AOD is 3.0 mL O\textsubscript{2} · kg\textsuperscript{-1} · mM\textsuperscript{-1}. Many researchers use this value to estimate the anaerobic energy metabolism from ΔbLa. However, this coefficient was calculated by having subjects perform arm or leg crank exercises at submaximal intensity (80% VO\textsubscript{2}·max). As the phosphocreatine stored in muscle is depleted during maximal exercise and the subject reaches the exhaustion point (supramaximal exercise), it is predicted that anaerobic energy metabolism produced by the ATP-CP system and the metabolic contribution of lactic-acid production and resynthesis are more than those produced during submaximal exercise. Additionally, anaerobic energy metabolism varies according to exercise pattern (i.e. cycling vs. running). Furthermore, it is possible that both the contribution of anaerobic energy metabolism and the lactic acid resynthesis capacity vary with competitive level (i.e. athlete vs. recreational). Thus, the conventional coefficient may underestimate the relationship between ΔbLa and AOD during supramaximal running of athletes.

The running intensity during an 800m run exceeds 100% VO\textsubscript{2}·max, and aerobic and anaerobic energy metabolisms contribute 60% and 40%, respectively, of the overall energy expended during an 800m run (Hill, 1999). Therefore, a superior energy metabolism capacity is essential for better performance. Particularly, the anaerobic energy metabolism contributes before as well as after increased oxygen uptake during an 800m run. Therefore, the energy metabolism required to resynthesize lactic acid...
is significant during an 800m run. It is therefore consid-
ered that middle-distance runners have a high anaerobic
energy metabolism and lactic acid resynthesis capacity,
and AOD per 1 mM of ΔbLa in such runners would be
different from data obtained using the values in previous
studies.6-9).

The purpose of this study was to clarify the estimated
expression of AOD by using ΔbLa from the relationship
between MAOD and ΔbLa during supramaximal running
of middle-distance runners.

Materials and Methods

Subjects. Eleven male middle-distance runners (age:
19.6 ± 0.9 years, height: 170.0 ± 4.8 cm, body weight:
58.5 ± 2.9 kg, body fat: 7.5% ± 1.2%, 800m season best
time: 1’52”9 ± 2”0, equivalent to an average velocity over
800m of 425.3 ± 7.3 m·min⁻¹; Table 1) took part in this
study. After being informed of the purpose of this study,
all subjects provided written informed consent, prior to
participation. The study was approved by the Research
Ethics Committee of the University of Tsukuba Graduate
School of Comprehensive Human Sciences (Issue Num-
ber: 27–27).

Experimental protocol and calculated values. All sub-
jects performed three running tests. The subjects ran on
a treadmill (ORK-7000; Ohtake-Root Kogyo Co., Ltd,
Iwate, Japan) at a 1% grade. All tests were performed in
the afternoon.

Maximal test. The subjects performed six-stage intermit-
tent incremental load running (3-min running and 2-min
rest) to measure their LT intensity (LTI). The initial stage
velocity was 210m ·min⁻¹ (only one subject started at
170m ·min⁻¹) and was increased by 20m ·min⁻¹ at each
stage. After six-stage running, the subjects rested for 5
min and then performed continuous incremental load run-
ning with the velocity increased by 10m ·min⁻¹ per min
until the subjects reached exhaustion to measure their
V̇O₂max. Exhaustion was defined as when two of the fol-
lowing factors occurred: (1) subjects reached their age-
predicted maximal heart rate (HR) (≥220 bpm – age in
years), (2) the respiratory exchange ratio (RER) exceeded
1.15 or (3) bLa exceeded 8.00 mmol ·L⁻¹.

Submaximal test. This test was performed 2 or 3 days
after the maximal test to measure each subject’s V̇O₂ at
65%, 70%, 75%, 80%, 85% and 90% V̇O₂max intensity.
The subjects ran for 4 min at 100m ·min⁻¹ as a warmup

<table>
<thead>
<tr>
<th>variables</th>
<th>units</th>
<th>mean (±SD) values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>years</td>
<td>19.6 ± 0.9</td>
</tr>
<tr>
<td>Height</td>
<td>cm</td>
<td>170.0 ± 4.8</td>
</tr>
<tr>
<td>Body weight</td>
<td>kg</td>
<td>58.5 ± 2.9</td>
</tr>
<tr>
<td>Body fat</td>
<td>%</td>
<td>7.5 ± 1.2</td>
</tr>
<tr>
<td>800-m running</td>
<td>m·min⁻¹</td>
<td>425.3 ± 7.3</td>
</tr>
<tr>
<td>V̇O₂max</td>
<td>mL·kg⁻¹·min⁻¹</td>
<td>66.1 ± 4.0</td>
</tr>
<tr>
<td>vV̇O₂max</td>
<td>m·min⁻¹</td>
<td>320.2 ± 16.4</td>
</tr>
<tr>
<td>LTI</td>
<td>%V̇O₂max</td>
<td>81.4 ± 4.7</td>
</tr>
<tr>
<td>vSRT</td>
<td>m·min⁻¹</td>
<td>389.0 ± 12.4</td>
</tr>
<tr>
<td>MAOD</td>
<td>mLO₂·kg⁻¹</td>
<td>56.6 ± 6.0</td>
</tr>
<tr>
<td>ΔbLa</td>
<td>mmol·L⁻¹</td>
<td>9.9 ± 1.1</td>
</tr>
<tr>
<td>MAOD·ΔbLa⁻¹</td>
<td>mLO₂·kg⁻¹·M⁻¹</td>
<td>5.8 ± 0.5</td>
</tr>
</tbody>
</table>

Note: V̇O₂max: maximal oxygen uptake, vV̇O₂max: velocity of maximal oxygen uptake, LTI;
lactate threshold intensity, vSRT: velocity of supramaximal running test, MAOD: maximal ac-
cumulated oxygen deficit, ΔbLa: accumulated blood lactate concentration, MAOD·ΔbLa⁻¹;
maximal accumulated oxygen deficit per accumulated blood lactate concentration.
and at each intensity, calculated according to the maximal test results, with 2-min rests between each velocity.

Supramaximal test. This test was performed on the same day as the submaximal test to measure MAOD, and bLa confirmed that the subjects had recovered to a resting state (after approximately 1-2 hours [h] rest). Each subject chose his own running velocity (121.6% ± 4.6% VO2max; velocity of supramaximal running test: vSRT) at which they reached exhaustion after 2 min[12].

Experimental instruments and measurement methods. Expired gas was measured by VO2, carbon dioxide excretion (VCO2), pulmonary ventilation (VE) and RER by using the breath-by-breath computerized standard open circuit technique with an expired gas analyzer (AE310-S Aero Monitor; Minato Medical Science Co., Ltd, Osaka, Japan). The gas analyzer and flow sensor were calibrated by using calibration gas (air equivalent: 21.00% O2, 0.03% CO2, balance N2, exhalation equivalent: 15.00% O2, 5.00% CO2, balance N2), and a flow calibrator (2 LPM), respectively. Experiments were performed with the measurement room being continuously ventilated. Before the test, after each running stage and after 1-, 3- and 5-min of exercise to exhaustion, a fingertip blood sample was taken for bLa measurement (1500 SPORT Lactate Analyzer; Yellow Springs Inc., Yellow Springs, OH, USA). HR was measured by using an HR monitor (Polar RCX5; Polar Electro Japan, Tokyo, Japan). Laboratory temperature and humidity were controlled at 24-26°C and 50-60%, respectively, with continuous ventilation throughout the experiment.

Data analysis. VO2max was defined as the highest oxygen uptake during 1 min in the continuous incremental load test. Velocity at VO2max (vVO2max) was calculated by substituting VO2max into the velocity-VO2 regression equation from the intermittent incremental load test data. Velocity at LT (vLT) was determined by using lactate analysis software (Lactate-E)[13]. LTI was determined from vLT and vVO2max.

The velocity-VO2 regression of the submaximal test was determined from seven points: 65, 70, 75, 80, 85 and 90% VO2max intensity and the 5.1 mLO2·kg⁻¹·min⁻¹ y-intercept[14]. MAOD was calculated by integrating the difference between actual oxygen and estimated oxygen uptakes (oxygen demand) from running speed extrapolation in the supramaximal test to the velocity-VO2 regression of the submaximal test. The difference in bLa concentration before and after the supramaximal test was defined as ΔbLa.

Statistical analysis. All statistical analyses were performed using SPSS version 22 (SPSS, Inc., Chicago, IL, USA). The relationships between variables were investigated using Pearson’s correlation coefficient. Data are expressed as the mean ± standard deviation. The significance level was set at p < 0.05.

Results
The results of aerobic and anaerobic capacities are shown in Table 1. The VO2-velocity regression line calculated from the submaximal test showed strong correlation (r² = 0.9965 ± 0.0029). The subjects ran 134.5 ± 11.0 seconds [s] at 389.0 ± 12.4m · min⁻¹ during the supramaximal test. MAOD and ΔbLa were 56.6 ± 6.0 mLO2·kg⁻¹ and 9.9 ± 1.1 mmol · L⁻¹, respectively. A significant positive relationship was observed between MAOD and ΔbLa (r = 0.73; Fig. 1). The regression line equation between MAOD (y) and ΔbLa (x) was y = 5.8 ± 0.5 mLO2·kg⁻¹ · mM⁻¹, and the coefficient of variation was 8.0%. In addition, there were significant negative relationships between MAOD ·ΔbLa−1 and both 800m running velocity and vSRT (r = -0.76 and -0.64, respectively; Fig. 2). On the other hand, neither MAOD nor ΔbLa were found to have a relationship with either 800m running velocity or vSRT (Table 2). MAOD ·ΔbLa−1 was not related to running time (r = -0.12) and physiological variables such as VO2max (r = -0.06), vVO2max (r = -0.44), LTI (r = 0.18), MAOD (r = 0.25) and ΔbLa (r = -0.48).

Discussion
The major finding of this study was that there was a significant positive relationship between MAOD and ΔbLa during supramaximal running of athletes; AOD per 1 mM of ΔbLa was determined to be 3.58 mLO2·kg⁻¹ · mM⁻¹ from the regression line equation. The AOD per 1 mM of ΔbLa has been considered to be 3.0 mLO2·kg⁻¹ · mM⁻¹ by many researchers[6-9]. However, our study showed that the value was 19% higher, which suggested that use of the conventional coefficient underestimates research results obtained during supramaximal running of competitive athletes. We assumed that this difference depends on the exercise pat-
tern and competitive level of the subjects.

di Prampero & Ferretti15 showed that AOD per 1 mM of ΔbLa was 2.7-3.3 mLO₂·kg⁻¹·M⁻¹ based on the results of Cerretelli et al.10, which clarified the relationship between AOD and ΔbLa during 5-min arm or leg crank exercise at 80% VO₂max intensity. On the other hand, the present study showed that AOD per 1 mM of ΔbLa was 3.58 mLO₂·kg⁻¹·M⁻¹, as determined from the relationship between MAOD and ΔbLa during 134.5 ± 11.0 s supramaximal running at 121.6 ± 4.6% VO₂max intensity. The anaerobic energy metabolism is recruited both before and after the increased oxygen uptake during supramaximal exercise relative to the uptake during submaximal exercise, so the contribution of anaerobic energy metabolism is larger. The anaerobic energy metabolism in running is greater than that during cycling because of more active muscle mass11. Cycling causes an isometric motion in the lower limbs that requires power, but the upper extremities do not work much. On the other hand, running is a stretch shortening action in the lower limbs, which has a rest phase when the body is in flight, and causes dynamic upper extremity motion11. In addition, Cavanagh and Kram15) demonstrated that greater eccentric muscle action with stretch-shortening action during running decreases the recruitment of type II motor units compared to cycling. These differences may resynthesize more lactic acid during running than during cycling. Furthermore, it is assumed that middle-distance runners have higher recruitment of muscle mass and lactic acid resynthesis capacity than recreational runners. These factors increased the AOD per 1 mM of ΔbLa observed in the present study relative to the values in previous research.

MAOD · ΔbLa⁻¹ is 5.8 ± 0.5 mLO₂·kg⁻¹·M⁻¹, which is the same value reported in the study of Hill and Vingren11 that clarified MAOD · ΔbLa⁻¹ during supramaximal running (3-, 5- and 7-minutes) of recreational runners. It is noted that MAOD · ΔbLa⁻¹ is larger than AOD per 1 mM of ΔbLa as 3.0 or 3.58 mLO₂·kg⁻¹·M⁻¹, because it includes the anaerobic energy metabolism provided by the ATP-CP system. The y-intercept of the regression line equation is 18.6 mLO₂·kg⁻¹, which corresponds to the anaerobic energy metabolism provided by the ATP-CP system estimated from the body weight and body fat of subjects. However, the present study did not evaluate the muscle mass of the subjects. In the future, a more accurate calculation of AOD per 1 mM of ΔbLa by evaluating muscle mass and the amount of stored phosphocreatine is needed.

The surprising result in the present study is that a significant negative relationship was observed between MAOD · ΔbLa⁻¹ and 800m running velocity. Thus, runners with smaller MAOD · ΔbLa⁻¹ should have better 800m running velocity. On the other hand, neither MAOD nor ΔbLa was found to be related to 800m running veloc-

**Table 2.** Correlation coefficient (p value) between anaerobic energy metabolism capacities and 800-m running velocity and vSRT.

<table>
<thead>
<tr>
<th>800-m running velocity</th>
<th>vSRT</th>
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<tbody>
<tr>
<td>MAOD</td>
<td>0.41 (0.22)</td>
</tr>
<tr>
<td>ΔbLa</td>
<td>0.18 (0.60)</td>
</tr>
</tbody>
</table>

Note: vSRT; velocity of supramaximal running test, MAOD; maximal accumulated oxygen deficit, ΔbLa; accumulated blood lactate concentration.
ity in this study, in contrast to the findings of many previous studies\(^2\)\(^4\). The reason for this difference may be the subjects’ running performance. Both females and males were included in the previous study, which assessed the relationship between MAOD and 800m running performance, and there was a heterogeneous performance level. However, only males were included in the present study, and the performance level was homogeneous. Our results suggest that MAOD · ΔbLa\(^{-1}\) is a useful physiological variable for estimating 800m running performance among homogeneous well-trained subjects. In addition, the variable for estimating 800m running performance was included in the previous study, which assessed the relationship between MAOD and 800m running performance, and there was a heterogeneous performance level. However, only males were included in the present study, and the performance level was homogeneous. Our results suggest that MAOD · ΔbLa\(^{-1}\) is a useful physiological variable for estimating 800m running performance among homogeneous well-trained subjects. In addition, MAOD · ΔbLa\(^{-1}\) may be affected by supramaximal running velocity because it has a negative relationship with vSRT. However, no significant relationship was observed between MAOD · ΔbLa\(^{-1}\) and other physiological variables, which suggests that the capacity of MAOD · ΔbLa\(^{-1}\) is not affected or only weakly affected by other physiological variables. MAOD is the amount of anaerobic energy produced by phosphocreatine and glycogen metabolism pathways; this study clarified that lower MAOD per ΔbLa resulted in greater 800m running performance. However, the phosphocreatine level in muscle has an upper limit. Therefore, it is suggested that an increased contribution of anaerobic energy from glycogenesis results in superior 800m running performance. In this study, the evaluation of physiological variables and performance level of subjects was limited and a detailed mechanism could not be considered.

**Conclusion**

This study clarified the estimated expression of AOD by using ΔbLa from the relationship between MAOD and ΔbLa during supramaximal running of athletes. The results showed that AOD per 1 mM of ΔbLa of athletes was 3.58 mLO\(_2\)·kg\(^{-1}\), which was 19% higher than the conventional coefficient value.

**Conflict of Interests**

The authors declared that they have no conflict of interest in the authorship and publication of this contribution.

**References**


