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ORIGINAL ARTICLE

Maximal accumulated oxygen deficit is influenced by chronological age and is related to intensity of VO_{2PEAK}

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Abstract

Purpose This study aimed to verify the influence of chronological age on maximal accumulated oxygen deficit (MAOD) and the correlations with maximal oxygen uptake (VO_{2PEAK}) and intensity (vVO_{2PEAK}).

Methods Thirty-one male athletes underwent an incremental exercise test involving 10 submaximal efforts (50–95% of velocity corresponding to VO_{2PEAK} [vVO_{2PEAK}]) and one supramaximal effort at 110% of vVO_{2PEAK} to determine MAOD. We analyzed a combined group ($n=31$) and two groups according to age (G1 = 15.5 ± 0.5; G2 = 36.0 ± 7.9 years).

Results The values of absolute VO_{2PEAK} (4.3 ± 0.4 L·min^{-1}) and vVO_{2PEAK} (15.9 ± 1.7 km·h^{-1}) were higher in G2 than those in G1 (3.5 ± 0.3 L·min^{-1}; 14.6 ± 0.9 km·h^{-1}). Individuals in G1 had absolute and relative values of MAOD (2.4 ± 0.7 L; 35.1 ± 11.1 mL·kg^{-1}) lower than those in G2 (3.9 ± 0.9 L; 46.8 ± 10.9 mL·kg^{-1}). Correlations between MAOD and performance during the experimental protocol were tested; VO_{2PEAK} and vVO_{2PEAK} yielded correlations with performance ($n=31$; $r=0.56$; $r=0.60$). Moreover, when corrected for chronological age, we detected correlations between absolute and relative values of MAOD and VO_{2PEAK} ($r=0.42$; $r=0.61$) and vVO_{2PEAK} ($r=0.43$; $r=0.56$).

Conclusions The MAOD is influenced by chronological age and is related to VO_{2PEAK} and vVO_{2PEAK} independent of age.

Keywords MAOD · Age · Anaerobic · Capacity · Fitness · Performance · Sports

Introduction

Success in many athletic events (e.g., running, cycling, swimming, soccer) is partially dependent on energy supply. This energy is provided via the hydrolysis of adenosine triphosphate (ATP), which is liberated by aerobic and anaerobic metabolism. When high-intensity activities are performed, the contribution of the anaerobic pathways increases (e.g., phosphagens and glycolysis) [1].

The assessment of phosphagen and glycolytic metabolism can be performed using maximal accumulated oxygen deficit (MAOD). This method quantitatively expresses the energy provided by the anaerobic during a supramaximal exhaustive test [2, 3]. Although the MAOD has received some criticism [3], the method is accepted as an estimation of anaerobic capacity [4]. The MAOD has been accepted because it is consistent across different genders [5, 6], training levels [7], types of training [8, 9], caffeine ingestion levels [10, 11], creatine levels [12], and active muscle mass [7, 13, 14]. It is also related to lactate production [15, 16], sensitive to glycogen depletion [17], and can be affected by

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the time of day [18]. The method has good reproducibility and reliability [19–21].

Adults have better anaerobic performance than children [22, 23], one explanation to this, is that during the transition from childhood to adulthood the anaerobic contribution to energy supply might increase due to augments in the levels of glycolytic enzymes such as phosphofructokinase (PFK), lactate dehydrogenase (LDH), and phosphorylases [22]. However, this evidence is yet to be clarified [24]. Adults have an increased oxygen deficit and debt, blood lactate concentration, muscle H^+ level, muscle glycogen reserves, phosphocreatine (PC) stocks, and testosterone levels [22]. These factors combine to improve performance at shorter exercise durations and higher intensities in adults. Moreover, the concentration of noradrenaline seems to be dependent on chronological age [25] and can participate in creatine metabolism, mainly through the stimulation of net creatine uptake preferentially by β_2 receptors probably via a cyclic AMP-dependent mechanism [26, 27]. Besides these evidences, no study has investigated whether MAOD is sensitive to chronological age. As MAOD is a widely accepted method to estimate anaerobic capacity indirectly, the differences between groups would confirm that MAOD is influenced by physiological and hormonal modifications.

Moreover, years ago it was shown that incidence of plateau at VO_{2MAX} is dependent on anaerobic capacity [28], evidencing that the tolerance to incremental exercise is dependent on anaerobic capacity. About this evidence, Shephard [29] criticized that few subjects reached their definition of an oxygen consumption plateau. Thus, the aim of the present study was to verify the influence of chronological age on MAOD and correlate it to intensity of peak oxygen consumption (vVO_{2PEAK}). Our hypotheses were that MAOD would: (1) change with age due to physiological and hormonal modifications, and (2) be correlated with vVO_{2PEAK}.

Methods

Subjects

Thirty-one male athletes (15–50 years; height 165–191 cm; weight 58–98 kg) participated in this study. All the athletes had performed at least 2 years of systematic training and had participated in state and national competitions of the triathlon, running and soccer (Table 1). For the interests of the study, we separated the athletes into two groups based on chronological age: G1 ($n = 16$, ranging 14–18 years) included younger athletes and G2 ($n = 15$, ranging 19–55 years). In some cases, the analyses were performed in a combined group ($n = 31$). All procedures were approved by the University's Institutional Review Board for Human Subjects (Human Research Ethics Committee) and were conducted according to the Declaration of Helsinki. Athletes and their parents, when pertinent, were informed about the experimental procedures and risks and signed an informed consent forms before their participation in the study. This study was performed in accordance with international ethical standards [30].

Experimental procedures

The experimental procedures for this study were performed over a 6-day period, with a minimum interval of 24 h between each test in both groups. During the evaluation period, before the determination of MAOD on the first day, the participants underwent an incremental exercise test

Table 1 Physical characteristics of groups and their values measured during the incremental exercise test ($n = 31$)

Variable	G1 ($n = 15$)			G2 ($n = 16$)			Combined ($n = 31$)		
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	SD	95% CI
Age (year)	15.5	0.5	15.2–15.8	36.0	7.9*	31.8–40.2	26.1	11.8	21.8–30.4
Height (cm)	174.6	7.5	170.4–178.8	178.6	6.7	175.1–182.2	176.7	7.3	174.0–179.3
Body mass (kg)	69.1	6.7	65.4–72.8	84.4	9.5	79.3–89.5	77.0	11.3	72.9–81.2
VO_{2MAX} ($L \cdot min^{-1}$)	3.5	0.3	3.4–3.7	4.3	0.4*	4.1–4.6	3.9	0.5	3.7–4.1
VO_{2MAX} ($mL \cdot kg^{-1} \cdot min^{-1}$)	51.4	3.9	49.3–53.6	52.1	5.9	48.9–55.4	51.8	5.0	49.9–53.6
vVO_{2MAX} ($km \cdot h^{-1}$)	14.6	0.9	14.1–15.1	15.9	1.7*	15.0–16.8	15.3	1.5	14.7–15.8
CR	1.2	0.1	1.1–1.3	1.1	0.1	1.1–1.2	1.1	0.1	1.12–1.2
HH (bpm)	191	10.3	185–196.7	184.6	10.3	179.1–190.1	187.7	10.6	183.8–191.6
% HH	93.4	5.0	93.4–90.6	97.5	6.6	93.9–101	95.5	6.1	93.2–97.8
$[La^-]_{PEAK}$ (mM)	8.4	3.0	6.5–10.5	9.4	3.0	7.8–11.0	9.0	3	7.8–10.2

VO_{2MAX} maximal oxygen consumption, *vVO_{2MAX}* minimal velocity which VO_{2MAX} was attained, *CR* coefficient respiratory, *HH* heart hate, *% HH* perceptual of heart hate expected for age, *$[La^-]_{PEAK}$* lactate concentration

*Observed difference between G1 and G2 $p < 0.05$

(IET) to measure the minimal velocity at which maximal oxygen consumption was attained (vVO_{2PEAK}). From day 2 to 6, the athletes performed 10 submaximal efforts (50–95% vVO_{2PEAK}) and one supramaximal effort corresponding to 110% of vVO_{2PEAK} for the determination of MAOD. Importantly, 10 submaximal exercise bouts were performed for the construction of a robust VO_2–velocity relationship to increase the validity and reliability of the results [3].

Respiratory and cardiac variables

The submaximal and supramaximal efforts used to determine MAOD were performed on a running treadmill. Respiratory and ventilatory variables were monitored breath-by-breath using a metabolic analyzer (Quark-PFT [Cosmed, Italy]). The gas analyzer was calibrated before each effort using known gas samples and the spirometer was calibrated according to the manufacturer's specifications using a 3-L syringe (Hans Rudolf 5530). The respiratory and ventilatory data were smoothed to remove outliers and interpolated to obtain values for each second using the software OriginPro 8.5 (OriginLab Corporation, Microcal, Massachusetts, USA). In addition, during all efforts, heart rate was monitored continuously using the interface of the gas analyzer.

Incremental exercise test

The IET was performed to measure the maximal oxygen consumption (VO_{2PEAK}) and vVO_{2PEAK}. The initial velocity corresponded to 9 $km \cdot h^{-1}$ and increments of 1 $km \cdot h^{-1}$ were added every 2 min until voluntary exhaustion was reached. VO_{2PEAK} was defined as the highest average VO_2 over the last 30 s of the test while considering at least three criteria: volitional exhaustion; blood lactate level $\geq$ 8.0 mM; heart rate (HR) $\geq$ age-predicted maximal HR (220-age); and respiratory exchange ratio $\geq$ 1.10. vVO_{2PEAK} was considered as the lower velocity at which VO_{2PEAK} was achieved.

Maximal accumulated oxygen deficit

Ten submaximal efforts were performed during 7 min. Each effort was performed at intensities from 50 to 95% of vVO_{2PEAK} [3]. In each evaluation session, two submaximal efforts were performed after allowing a recovery of 15 min to allow VO_2 to return to resting levels. The mean VO_2 during the last minute of each bout was assumed as the steady-state VO_2 for the corresponding velocity and was used in the construction of the velocity–VO_2 relationship. In addition, the athletes performed a supramaximal effort corresponding to 110% of the vVO_{2PEAK} to measure the time to exhaustion (*t*lim) and VO_2 during supramaximal exercise.

Linear regression was performed based on the velocity–VO_2 relationship to estimate the oxygen demand at 110% of vVO_{2PEAK} (D_ET) using 10 submaximal bouts. The linear regression model was constructed by fixing the *y*-intercept at basal oxygen consumption values [2, 3]. MAOD was taken as the difference between the area of D_ET (estimated by the product between the D_ET by the *t*lim) and the integral determined by the trapezoidal method of VO_2 observed throughout the exercise performed at 110% of vVO_{2PEAK}.

Lactate concentrations

Blood samples were taken from the earlobes in 25-µL heparinized capillary tubes after the IET and monitored at minutes 1, 3, 5, and 7 to determine the peak lactate concentration ($[La^-]_{PEAK}$) using a lactate analyzer (YSI 1 500 Sport, Yellow Spring Instruments, Ohio, USA).

Statistical treatment

The Shapiro–Wilk test was used to assess the normality of data and Levene's test was used to assess homogeneity. The descriptive results are presented as means, standard deviations, and 95% confidence intervals (95% CI). The possible differences between G1 and G2 in terms of IET, demand estimated by regression, *t*lim, and MAOD values were assessed using a *t* test for independent samples. Pearson's product and partial correlation were used to determine the strength and direction of the relationships among performance indices and chronological age. Partial correlations were used to control for the possible effect of chronological age on aerobic and anaerobic indices. This was performed while controlling for the possible causal link among variables because the control variable (i.e., chronological age) could interfere with the analysis. The magnitudes of the relationships were expressed as standardized scores (*r*): very weak (0.0–0.2), weak (0.2–0.4), moderate (0.4–0.7), strong (0.7–0.9), or very strong (0.9–1.0) [31]. All the analyses were performed using SPSS software version 20.0 (IBM, Armonk, NY) with a significance level of 5%.

Results

At all submaximal intensities, oxygen consumption remained stable in the last minute and the linear coefficient obtained from the relationship between intensity and steady-state O_2 was $\sim 0.94 \pm 0.04$ $L \cdot min^{-1} \cdot km \cdot h^{-1}$ in all groups. The residual values of intercept and slope of regression were obtained in G1, G2 and combined group, respectively (2.4 ± 1.1 $mL \cdot kg^{-1} \cdot min^{-1}$, 0.4 ± 0.6 U.A.; 3.0 ± 0.8 $mL \cdot kg^{-1} \cdot min^{-1}$, 0.3 ± 0.7 U.A.; 2.7 ± 0.9 $mL \cdot kg^{-1} \cdot min^{-1}$, 0.3 ± 0.5 U.A.). The value of *t*lim was 205.2 ± 97.1 s in G1 and 160.6 ± 40.6 s in G2, and the group average was 182.3 ± 67.1 s at an effort

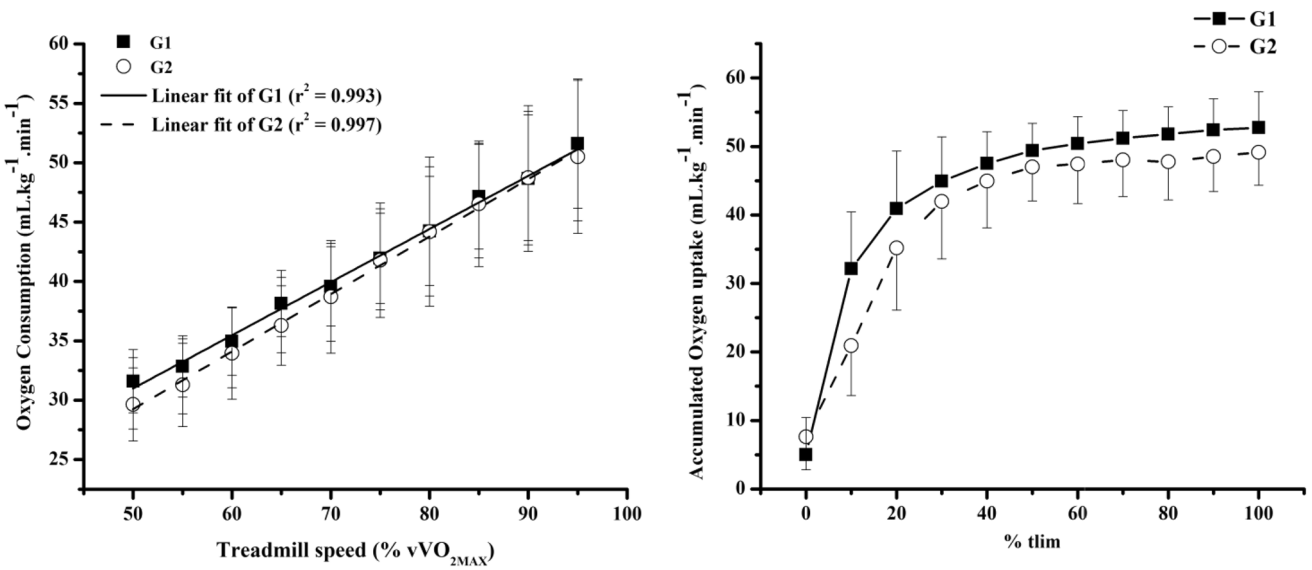

Fig. 1 Oxygen kinetics during maximal accumulated oxygen deficit determination in G1 and G2

Table 2 Values of the maximum accumulated oxygen deficit (MAOD) expressed in absolute (L) and relative to body weight ($MAOD_{BW}$) in G1, G2 and group ($n=31$)

	G1 ($n=15$)			G2 ($n=16$)			Group ($n=31$)		
	Mean	SD	95% CI	Mean	SD	95% CI	Mean	SD	95% CI
MAOD (L)	2.4	0.7	2.0–2.8	3.9*	0.9	3.4–4.4	3.1	1.1	2.7–3.5
$MAOD_{BW}$ (mL·kg^{-1})	35.1	11.1	28.9–41.3	46.8*	10.9	41.0–52.6	40.6	12.1	36.1–45.1

*Observed difference between G1 e G2 $p<0.05$

corresponding to 110% of vVO_{2PEAK} (16.1 ± 1.0 km·h^{-1} in G1 and 17.3 ± 2.0 km·h^{-1} in G2). The oxygen consumption observed in the last minute of this effort in G1 (3.8 ± 0.5 L·min^{-1}) was not significantly different from the VO_{2PEAK} obtained in the IET (3.9 ± 0.5 L·min^{-1}). In G2, oxygen consumption in the last minute of *t*lim was equivalent to 95.2% (4.1 ± 0.4 L·min^{-1}) of that observed in the IET (4.3 ± 0.5 L·min^{-1}; $p<0.05$). The oxygen kinetics observed on submaximal regression and supramaximal effort (G1 and G2) for MAOD determination are presented in Fig. 1.

The description of absolute and relative MAOD values for each group, as well as the respective statistical difference between groups is shown in Table 2. Pearson's product demonstrated correlations between MAOD and performance indices that were independent of chronological age in three situations. The first was the correlation found among the relative values of MAOD and VO_{2PEAK} ($r=0.56$; $p=0.001$), while the second was found for the correlation of MAOD relative and absolute values with vVO_{2PEAK} ($r=0.60$; $r=0.50$; $p<0.01$, respectively). Moreover, the partial correlation, when corrected by chronological age, showed some significant relationships among performance indices and anaerobic capacity (Table 3).

Table 3 Correlation coefficients (*r*) obtained between the maximum accumulated oxygen deficit (MAOD) and performance indexes controlled by chronological age ($n=31$)

Corrected by chronological age	MAOD	
	(L)	(mL·kg^{-1})
VO_{2MAX} (L·min^{-1})	0.39*	0.17
VO_{2MAX} (mL·kg^{-1}·min^{-1})	0.42*	0.61**
vVO_{2MAX} (km·h^{-1})	0.43*	0.56*
Slope regression (*a*)	0.29	0.51**

*Significant correlation between the variables ($p<0.05$); ** significant correlation between the variables ($p<0.01$)

Discussion

The aims of the present study were to compare MAOD between young and adult athletes and to see how these values correlated with performance. The main findings of this study were as follows: (1) age played a role in MAOD, and (2) there were correlations among anaerobic capacity and aerobic indices even when MAOD was corrected for chronological age.

The effect of age on anaerobic capacity (i.e., MAOD) is an important issue because athletes of different ages often compete against each other in several events. In the last Olympic games (Rio 2016), the age of the participating athletes varied (e.g., between 13 and 62 years [Gaurika Singh and Julie Brougham]). In swimming, 19-year-old Rūta Meilutytė competed against 31-year-old Michael Fred Phelps. The age of track and field athletes varies between 24 and 34 years (Wayde van Niekerk and Justin Gatlin), while in cycling the age range is 20–37 years (Niek Kimmann and Rubens Donizete). Moreover, in all of the abovementioned sports, studies have been published regarding the relationship between performance indices and anaerobic capacity [4, 32–35].

Additionally, no study has been conducted to assess the effect of chronological age on MAOD. Some studies demonstrating the influence of age on anaerobic metabolism have been published over the past century. Margaria et al. [36] demonstrated that anaerobic power was lower in children than that in adolescents and adults. The authors found that anaerobic power increases with age and peaks at 20–30 years of age. Inbar and Bar-Or [22] observed lower anaerobic performance, lower maximal lactate concentrations in muscle and blood, lower rates of anaerobic glycolysis, and lower levels of acidosis at maximal exercise in children [22]. Mercier et al. [37] found that maximal anaerobic power increased from childhood to adolescence (from 11 to 19 years of age). However, it is not possible to extrapolate anaerobic power for the evaluation of modifications in anaerobic capacity since some studies have demonstrated that anaerobic power does not represent capacity [16, 38, 39].

The activity of glycolytic enzymes (PFK, LDH, and phosphorylase) [22], oxygen deficit and debt, blood lactate concentration, muscle H^+ level, muscle glycogen reserves, PC stores [22], and noradrenaline concentration [25] appear to differ between children and adults. The quickness to access the glycogen and PC reserves could be faster in adults and this can somehow save energy originated from aerobic metabolism and this way, increase the *t*lim, this is unknown, mainly because do not be found evidence that support it.

However, it appears that the development of aerobic fitness in terms of absolute and relative values (VO_{2MAX}) occurs in mature and non-mature young people and that absolute values are good predictors of performance [40]. It seems that as chronological age increases, the relative values of VO_{2PEAK} and MAOD ($r=0.61$) determine performance at the maximal velocity of the IET (vVO_{2PEAK} vs. VO_{2PEAK}; $r=0.71$; $p<0.001$).

Only one previous study has verified the interdependence of MAOD and these aerobic indices. Gordon et al. [28] verified that the plateau of maximal oxygen uptake is dependent on anaerobic capacity and suggested that different values of anaerobic capacity may determine the possible variations in the time required to complete the IET. The time required to complete the IET in the present study was 873.5 ± 182.4 s (i.e., 14.5 ± 3.0 min). When controlling for age, we did not identify a partial correlation between the time required to complete the IET and anaerobic capacity ($r=0.27$; $p=0.07$). The possible explanation for this is that with increasing age, fatigue and pain during IET can be ameliorated by enhancement of anaerobic energy capacity [41]. However, this is probably not due to the efficiency of the removal of metabolites and neuromuscular pumping ability. It is possible that in adults, the energy required for performing the IET is provided in part by anaerobic metabolism.

Conclusions

In conclusion, the findings of the present study support the hypothesis that MAOD is influenced by chronological age. Moreover, anaerobic capacity is related to obtaining the maximal oxygen uptake and velocity of maximal oxygen uptake during the IET independently of age.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures were approved by the University's Institutional Review Board for Human Subjects (Human Research Ethics Committee - 78855516.9.0000.5659) and were conducted according to the Declaration of Helsinki. Avaliable in http://plataformabrasil.saude.gov.br/login.jsf.

Informed consent Informed consent was obtained from all individual participants included in the study.

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