Different $\dot{V}O_{2max}$ Time-Averaging Intervals in Swimming

Authors

R. J. Fernandes[1, 2], K. de Jesus[1], C. Baldari[3], K. de Jesus[1], A. C. Sousa[1], J. P. Vilas-Boas[1, 2], L. Guidetti[3]

Affiliations

[1] Centre of Research, Education, Innovation and Intervention in Sport, Faculty of Sport, University of Porto, Portugal
[2] Porto Biomechanics Laboratory, University of Porto, Portugal
[3] Department of Health Sciences, University of Rome "Foro Italico", Rome, Italy

Key words
- swimming
- maximal oxygen uptake
- time-averaging
- incremental protocol

Abstract

We aimed to determine the effect of sampling interval strategy on $\dot{V}O_{2max}$ assessment to establish a standard time averaging method that allows a better identification of the $\dot{V}O_2$ plateau incidence in swimming. To this end, 3 incremental protocols utilizing different step lengths for each sampling interval were used to compare $\dot{V}O_{2max}$ measurements. 11 trained male swimmers performed 3 repetitions of a front crawl intermittent incremental protocol until exhaustion (increments of 0.05 m.s^{-1}, with 30 s and 24–48 h intervals between steps and tests, respectively) with 200, 300 and 400-m step lengths. $\dot{V}O_2$ was directly measured, and 6 sampling intervals were compared: bxb and averages of 5, 10, 15, 20 and 30 s. Shorter sampling intervals ($\leq$15 s) allowed the highest incidence of the $\dot{V}O_2$ plateau, independent of the step lengths used; the 200 and 300-m step protocols accounted for higher percentage of $\dot{V}O_2$ plateau incidence, and higher $\dot{V}O_{2max}$ values, compared to the 400-m step protocol. As an optimal sampling interval should be used for the validation of the research findings, and considering that swimmers and coaches prefer less time-consuming protocols, the use of the 10 s time-average interval (once bxb and 5 s samplings present high variability) in a 200-m step incremental protocol for $\dot{V}O_{2max}$ assessment in swimming is suggested.

Introduction

Since the pioneer work of Liljestrand and Strestrom [23], who measured the oxygen uptake ($\dot{V}O_2$) of swimming in a lake, followed by sporadic studies in the 1940s [18] and 1960s [3], the measurement of cardiorespiratory parameters (ventilatory volume, heart rate, and, especially, $\dot{V}O_2$) have been a topic of swimming research (cf. the reviews [7, 16]). Expanding on these previous studies, $\dot{V}O_2$ measurement in swimming was frequently conducted in a flume or with a pulley system in a conventional pool, using a Douglas bag technique or a mixing chamber analyser. Looking for more ecological conditions, Toussaint et al. [36] presented a respiratory snorkel and valve system with low hydrodynamic drag, which allowed continuous $\dot{V}O_2$ measurement during conventional swimming in pools using swimmers of different levels [10, 11, 38].
As technology advanced, a portable gas analyser composed of a facemask, a flow meter, an O_2 gas analyser, and a telemetric receiver was developed (Cosmed K2, Rome, Italy), and newer versions appeared (equipped with a CO_2 analyser) that allowed breath-by-breath data acquisition in swimming (Cosmed K4b2, Rome, Italy) [11, 30]. The widespread availability of modern breath-by-breath gas exchange systems enabled the acquisition of data with greatest precision and temporal resolution [2, 8, 15], and the improved instrumentation and technology in breath-by-breath analysis allowed new approaches to study cardiorespiratory parameters in laboratory and field conditions [21, 31].
From the traditionally assessed cardiorespiratory parameters, maximal oxygen consumption ($\dot{V}O_{2max}$) has been lauded as an objective and reliable measure of the integrated maximal exercise response [25], and is associated with the exercise intensity related to one of the primary areas of interest in swimming training and performance diagnostic [3, 7, 11, 16, 22]. Despite being widely assumed as a standard of maximal aerobic power [7, 10, 11, 16], and commonly accepted as a prerequisite for excellence in swimming [11, 35], there is no consensus on standardized criteria to verify $\dot{V}O_{2max}$ attainment at the end of an incre-

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Correspondence
Prof. Ricardo J. Fernandes, PhD
Centre of Research Education, Innovation and Intervention in Sport
Faculty of Sport
University of Porto
4200 Porto
Portugal
Tel.: +351/22/5074 763
Fax: +351/22/5500 687
ricfer@fade.up.pt

mental exercise. In addition, the $\dot{V}O_2$ kinetics measurement using the breath-by-breath technology has been also used to evaluate one major swimming performance determinant – the energy cost – through the percentages of $\dot{V}O_{2max}$ at different step intensities [10, 11, 19, 30, 31].

Essential to the utilization and interpretation of breath-by-breath technology in $\dot{V}O_2$ related studies is the consideration of substantial inter-breath fluctuations of gas exchange during rest and exercise periods [1, 25], which do not represent variations in O_2 loading in the lung or its utilization in the exercising muscles [15]. In fact, when studying the $\dot{V}O_2$ response to a specific effort, it is essential to analyse the variability on the $\dot{V}O_2$ imposed by the chosen sampling interval [9]. Multiple analysis strategies have been applied to inter-breath fluctuations to remove or reduce this source of imprecision, particularly by averaging the data from up to 8 repetitions of the same step transitions [2], and averaging across breaths or within discrete time intervals [26].

The impact of inter-breath variability in gas exchange has been addressed mainly for the heavy intensity domain, predominantly for the most accurate determination of $\dot{V}O_{2max}$. Matthews et al. [24] and Myers et al. [26], for treadmill and ramp exercises (respectively), reported that ~20 % difference in $\dot{V}O_{2max}$ could be attributed to differences in the method of sampling interval gas exchange data, and that the greatest $\dot{V}O_{2max}$ values were systematically higher as fewer breaths were included in an average. Astorino et al. [1] and Astorino [2] reported that sampling intervals dramatically influenced the incidence of the $\dot{V}O_2$ plateau (the most used criterion for confirming the $\dot{V}O_{2max}$ attainment), and recommended short sampling intervals (≤ 15 s) when conducting incremental exercise to exhaustion. However, Midgley et al. [25] evidenced that short time-average intervals appear to be inadequate in reducing the noise in pulmonary $\dot{V}O_2$, resulting in artificially high $\dot{V}O_{2max}$ values. Furthermore, Hill et al. [15] reported high $\dot{V}O_{2peak}$ values at different intensities within the severe intensity domain when based on smaller sampling interval windows.

Specifically in swimming, the time-averaging method used to remove variation in breath-by-breath $\dot{V}O_2$ has remained neglected when assessing $\dot{V}O_{2max}$; in fact, only Sousa et al. [34] analysed the $\dot{V}O_{2max}$ variability (using 5 different time-averaging intervals), observing higher $\dot{V}O_2$ values for breath-by-breath sampling interval compared to time averages of 5, 10, 15 and 20 s in a 200-m all-out front crawl effort. Agreeing with the literature that the selection of optimal sampling interval strategy is fundamental to the validation of the research findings, as well as to the correct training diagnosis and posterior series intensity prescription, the aim of the present study was to establish a standard $\dot{V}O_{2max}$ time-averaging method that allows better identification of the incidence of the $\dot{V}O_2$ plateau. For that purpose, 6 of the most used time-average intervals were compared: breath by breath and averages of 5, 10, 15, 20 and 30 s. As well, assuming that the step lengths used in the swimming incremental protocol for $\dot{V}O_{2max}$ assessment might affect the final result (as reported for running and cycling by Kuipers et al. [20] and Hill et al. [15], respectively), a comparison between the rate of $\dot{V}O_{2max}$ appearance when using 200, 300 and 400-m length steps was also accomplished, as these distances are the ones most used in the specialized literature [10, 12, 19, 22, 28, 30, 38]. It was hypothesized that the $\dot{V}O_{2max}$ values would be greater when using shorter samplings intervals, particularly those ≤ 15 s, and that step lengths over 5 m duration (the 400-m steps) will imply a higher incidence of plateau in $\dot{V}O_2$ at $\dot{V}O_{2max}$.

Materials and Methods

Participants

11 trained male swimmers volunteered for this study and signed an informed consent form before participation began. Mean ± SD values for physical and performance characteristics were: 20.4 ± 2.5 years of age, 1.80 ± 0.06 m of height, 74.1 ± 4.1 kg of body mass, 11.3 ± 1.5 % of fat mass, 11.8 ± 3.2 years of training background, and 90.0 ± 4.1 % from the 200-m front crawl short course world record. Body mass and fat mass were assessed through the bioelectric impedance analysis method (Tanita TBF 305, Tokyo, Japan). All subjects were involved in systematic training (8–10 weekly training sessions) and competition programs – participating regularly in freestyle events. All the procedures were in accordance with the ethical standards proposed by Harriss and Atkinson [14].

Experimental procedure

Testing sessions took place in a 25-m indoor swimming pool, during the morning, at a room temperature of 28 °C and humidity of 55 %. Prior to the experiment, subjects were not engaged in high-intensity training sessions, and limited their training program to a single daily low-intensity swimming session. Swimmers performed, in a randomized order, 3 repetitions of a front crawl intermittent incremental protocol until exhaustion, each one with a different step length (200, 300 and 400-m); the protocol had velocity increments of 0.05 m/s, with 30 s rest intervals between steps, and an interval of 24–48 h between each repetition. Researchers and coaches defined the velocity of the last step of the protocol through the 400-m front crawl best time that swimmers were able to accomplish at that moment (using in-water starts and open turns); then, 6 successive 0.05 m/s were subtracted from the swimming velocity corresponding to the last step, allowing the determination of the mean target velocity for each step (for a more detailed description see Fernandes et al. [12]). Underwater pacemaker lights (GBK-Pacer, GBK Electronics, Aveiro, Portugal), placed on the bottom of the pool, were used to help swimmers keep an even pace along each step, and change accordingly to the pace differences between steps. Swimmers breathed through a respiratory snorkel and valve system (the new AquaTrainer Snorkel®, Cosmed, Rome, Italy, cf. [4]), connected to a telemetric portable gas analyzer (K4b^2, Cosmed, Rome, Italy). The K4b^2 apparatus was calibrated following the procedures described in the specialized literature [8, 11, 13, 22, 30]. Atmospheric pressure and ambient temperature were measured by the K4b^2 portable unit, and relative humidity was measured and manually reported to the K4b^2 before each test. Heart rate was monitored and registered continuously by a heart rate monitor system (Polar Vantage NV, Polar electro Oy, Kempele, Finland) that telemetrically emitted the data to the K4b^2 portable unit. Capillary blood samples were collected from the earlobe during the 30 s intervals, immediately at the end of exercise, and during the 1st and 3rd min of the recovery period (Lactate Pro, Arkay, Inc, Kyoto, Japan).

Data analysis

$\dot{V}O_2$ data analysis was centred in the step where $\dot{V}O_{2max}$ occurred. First, following Özyener et al. [27], occasional breath values were omitted from the analysis by including only those in-between ± 4 standard deviation regarding the mean $\dot{V}O_2$ value, once aberrant $\dot{V}O_2$ values typically arise due to some constraints caused by the valve system and by swimming characteristics (e.g., longer apnea moments during the turns). Afterwards, individual breath-by-breath $\dot{V}O_2$ responses were smoothed by using a 3-breath moving average and time-average [11] to produce a standard weighted response at 5, 10, 15, 20 and 30 s sampling intervals (an example of the $\dot{V}O_2$ kinetics during the incremental protocol using breath-by-breath and 15 s sampling intervals is displayed in ◉ **Fig. 1**). $\dot{V}O_{2max}$ was considered to be reached according to the occurrence of a plateau in $\dot{V}O_2$, i.e., differences of $\dot{V}O_2$ ≤ 2.1 ml.kg^{-1}.min^{-1} in the last 60 s of the step (between the final $\dot{V}O_2$ value and the closest neighbouring data point), despite an eventual further increase in swimming velocity (◉ **Fig. 1**); if this was not observed, secondary criteria were applied, namely high levels of blood lactate concentration ($\geq$8 mmol.l^{-1}), elevated respiratory exchange ratio ($r \geq 1.0$), elevated heart rate [90 % (220-age)], and an exhaustive perceived exertion, controlled visually and case-by-case (cf. [10, 11, 17, 22, 33]).

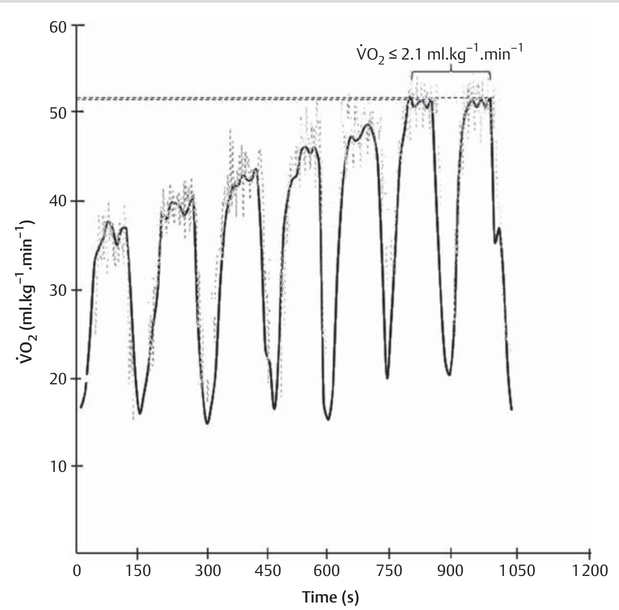

Fig. 1 Example of the $\dot{V}O_2$ kinetics along a swimming incremental intermittent protocol for $\dot{V}O_{2max}$ assessment using breath-by-breath and 15 s sampling intervals (dotted and continuous lines, respectively). The occurrence of a $\dot{V}O_2$ plateau during the 6th step is represented.

Statistical analysis

Data distribution was screened, and a non-normal distribution was observed through scatter plots and formal test (Shapiro-Wilk). $\dot{V}O_2$ values were presented as median and interquartile range, and differences between time sampling intervals were tested for significance using the Friedman Multiple Comparison Test; the observed Z-scores for the dependent variable are based on positive or negative ranks, and significant differences are obtained if Z-score is in the [−1.96 to 1.96] interval. In addition, the Kendall w rank correlation coefficient values were also given; the coefficient of concordance must be in the range $-1 \leq w \leq 1$, with higher values indicating a strong relationship. SYSTAT version 13.0 was used, and statistical significance was defined for $p < 0.05$.

Results

▼

Individual $\dot{V}O_{2max}$ values occurred mostly in the sixth rather than in the seventh step in the 200 (n = 6 vs. 5), 300 (n = 9 vs. 2) and 400-m (n = 10 vs. 1) step lengths protocols. At the steps where $\dot{V}O_{2max}$ was obtained, the following median ± IQR values of blood lactate concentration, respiratory exchange ratio, and heart rate were observed: 8.22 ± 1.11, 8.41 ± 1.54 and 8.17 ± 1.24 mmol.l^{-1}, 1.15 ± 0.05, 1.18 ± 0.01 and 1.17 ± 0.02, and 187.6 ± 6.0, 182.4 ± 5.6 and 180.8 ± 3.8 b.min^{-1}, respectively for the 200, 300 and 400-m step lengths protocols.

$\dot{V}O_{2max}$ values, assessed with different time sampling intervals (breath-by-breath and average of 5, 10, 15, 20 and 30 s) in the intermittent incremental protocol of 200, 300 and 400-m steps are displayed in ◉ **Table 1–3**, respectively. In ◉ **Table 1** it was observed that: (i) breath-by-breath presented greater values than sampling intervals of 10, 15, 20 and 30 s (Zscore = 3.23, p = 0.00, Kendall's W = 0.63; Zscore = 2.21, p = 0.00, Kendall's W = 0.63; Zscore = 2.98, p = 0.00, Kendall's W = 0.63; and Zscore = 3.04, p = 0.00, Kendall's W = 0.63, respectively); (ii) 5 s time average presented greater values comparing to those of 20 and 30 s (Zscore = 2.78, p = 0.00, Kendall's W = 0.63 and Zscore = 3.05, p = 0.00, Kendall's W = 0.63, respectively). In addition, breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals accounted for a percentage of $\dot{V}O_2$ plateau incidence of 27.2, 45.5, 72.7, 54.4, 18.1 and 18.1 %.

In ◉ **Table 2** the data for the 300-m step lengths protocol is displayed, being possible to observe that breath-by-breath presented a higher value than time average of 20 and 30 s

Table 1 Individual and median ± interquartile range (IQR) values of $\dot{V}O_{2max}$ (ml · min^{-1} · kg^{-1}) at the incremental protocol of 200-m steps using different sampling intervals.

Subjects	breath-by-breath	5 s	10 s	15 s	20 s	30 s
A	56.83	56.71	56.32	55.21	54.14	53.25
B	51.56	51.21	51.33	51.57	51.78	51.45
C	52.81	52.33	52.45	52.52	52.44	51.77
D	51.08	49.75	49.49	49.47	49.63	49.85
E	48.99	45.69	45.09	46.05	44.01	44.04
F	53.95	53.71	53.58	53.86	53.60	53.62
G	54.15	52.19	52.27	51.78	52.46	51.57
H	52.21	53.12	52.65	54.19	52.74	52.23
I	53.04	50.17	49.36	50.16	49.31	49.68
J	51.30	53.6	51.73	51.22	50.44	49.10
K	51.80	52.04	51.16	51.50	50.74	51.09
Median ± IQR	53.23 ± 2.21 [a, b, c, d]	52.13 ± 3.14 [c, d]	51.64 ± 3.31	51.15 ± 3.26	51.11 ± 3.21	51.08 ± 3.36

[a, b, c, d] Significantly different from time sampling interval of 10, 15, 20 and 30, respectively

Table 2 Individual and median ± interquartile range (IQR) values of $\dot{V}O_{2max}$ (ml · min^{-1} · kg^{-1}) at the incremental protocol of 300-m steps using different sampling intervals.

Subjects	breath-by-breath	5 s	10 s	15 s	20 s	30 s
A	56.22	56.27	52.70	52.04	54.31	55.06
B	53.97	53.80	53.43	53.53	53.71	53.33
C	56.56	56.35	55.50	56.12	56.32	54.68
D	49.11	51.16	54.11	50.80	52.83	52.80
E	53.71	47.20	46.50	46.05	46.70	47.19
F	50.78	51.02	50.97	51.23	50.66	50.42
G	52.50	53.32	52.17	50.26	51.32	50.69
H	53.50	51.05	51.13	50.62	48.50	48.24
I	54.46	53.65	53.91	53.13	50.31	50.68
J	52.13	51.94	51.23	51.25	49.04	49.11
K	51.98	51.67	51.81	51.89	51.89	51.35
Median ± IQR	52.89 ± 3.13 [a, b]	51.67 ± 2.80	51.88 ± 2.77	51.25 ± 2.99	51.01 ± 3.86	50.19 ± 2.90

[a, b] Significantly different from time sampling interval of 20 and 30, respectively

Table 3 Individual and median ± interquartile range (IQR) values of $\dot{V}O_{2max}$ (ml · min^{-1} · kg^{-1}) at the incremental protocol of 400-m steps using different sampling intervals.

Subjects	breath-by-breath	5 s	10 s	15 s	20 s	30 s
A	54.14	53.26	52.97	54.77	54.05	54.20
B	52.14	52.35	51.38	51.76	52.06	50.34
C	54.21	53.42	54.01	52.15	52.09	52.14
D	50.01	50.17	50.01	50.46	49.17	49.23
E	48.57	49.54	49.20	48.32	46.54	46.26
F	51.39	51.64	50.93	50.10	49.99	49.72
G	53.50	53.32	52.84	52.10	50.03	50.14
H	51.07	50.16	50.32	50.14	49.12	48.74
I	53.05	50.17	49.36	50.16	49.31	49.68
J	51.88	51.24	50.89	50.22	49.44	49.02
K	51.48	51.04	50.83	50.50	49.57	49.08
Median ± IQR	51.39 ± 2.81 [a, b]	51.64 ± 2.90 [a, b]	50.93 ± 3.30	50.46 ± 3.19	49.72 ± 2.64	49.13 ± 3.74

[a, b] Significantly different from time sampling interval of 20 and 30, respectively

(Zscore = 2.95, p = 0.02, Kendall's W = 0.54; Zscore = 1.96, p = 0.05, Kendall's W = 0.54). Finally, breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals accounted for a percentage of $\dot{V}O_2$ plateau incidence of 36.6, 45.5, 81.1, 54.4, 27.2 and 18.1 %.
In the 400-m step lengths protocol (**Table 3**) breath-by-breath and 5 s time-averaging presented greater values than time averages of 20 and 30 s (Zscore = 3.03, p = 0.00, Kendall's W = 0.58 and Zscore = 3.05, p = 0.00, Kendall's W = 0.58, respectively), and breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals accounted for a percentage of $\dot{V}O_2$ plateau incidence of 27.2, 36.3, 63.6, 45.5, 18.1 and 18.1 s.
Comparison between intermittent incremental protocols of 200, 300 and 400-m step lengths for the different studied $\dot{V}O_2$ sampling intervals evidenced that: (i) when using breath-by-breath data, $\dot{V}O_{2max}$ median value obtained in the 300-m protocol was higher than that from the 400-m test (Zscore = 2.24, p = 0.04, Kendall's W = 0.28); (ii) when using 5 s average, $\dot{V}O_{2max}$ value of the 200-m protocol was higher than that obtained in the 400-m protocol (Zscore = 2.34, p = 0.04, Kendall's W = 0.31); (iii) regarding the 10 s time-averaging, no differences were observed in $\dot{V}O_{2max}$ values between protocols; (iv) averaging of 15 s indicated higher $\dot{V}O_{2max}$ values in the 200-m protocol than when using 400-m steps (Zscore = 2.36, p = 0.02, Kendall's W = 0.29); (v) considering the time average of 20 s, both 200 and 300-m protocols registered higher $\dot{V}O_{2max}$ values than the protocol with 400-m steps (Zscore = 2.17, p = 2.17, Kendall's W = 0.47 and Zscore = 2.34, p = 0.02, Kendall's W = 0.47, respectively); (vi) lastly, when using 30 s time-averaging, both 200 and 300-m protocols registered higher $\dot{V}O_{2max}$ values than 400-m test (Zscore = 2.08, p = 0.03, Kendall's W = 0.55 and Zscore = 3.29, p = 0.00, Kendall's W = 0.55, respectively).

Discussion

To our knowledge, this is the first study that compared $\dot{V}O_{2max}$ values, and examined the incidence of the $\dot{V}O_2$ plateau, across various $\dot{V}O_2$ sampling intervals, trying to propose a judicious time-averaging method to be used in $\dot{V}O_{2max}$ assessment in swimming. As the selection of optimal sampling interval strategies is a topic of great interest in laboratory exercise testing (cf. [1, 2, 15]), and is fundamental to validate its findings, the pertinence of this study in swimming is perfectly justified; in fact, the determination of the best sampling interval for $\dot{V}O_{2max}$ assessment is essential for a correct aerobic training status diagnosis, and subsequent prescription of training.
The respiratory snorkel and valve system attached to the K4b2 was successfully used for swimming [6, 19, 22, 29, 30, 33], allowing swimmers to perform their movements without restrictions [33]. In fact, eventual differences in swimming velocity when comparing free swimming and swimming using the "old" AquaTrainer snorkel are not due to alterations in general kinematics or swimming efficiency but to the gliding phases after starts and turns [5]; moreover, according to the manufacturer, the new AquaTrainer snorkel used in the current study is light, hydrodynamic, ergonomic and comfortable. K4b2 apparatus has

been seen before as accurate and reliable [6], and the exclusion of occasional breath values over 4 ± SD $\dot{V}O_2$ values from the local mean significantly minimized occasional errant breaths in assessing $\dot{V}O_{2max}$ due to swallowing, coughing, sighing or some other reason unrelated to the physiological response of interest [13, 27]. In addition, the smoothing of individual breath-by-breath $\dot{V}O_2$ responses using a 3-breath moving average and time-average [11] allowed production of a standard weighted response at 5, 10, 15, 20 and 30 s sampling intervals, thereby reducing the "noise" and increasing the confidence of the parameter estimation.

The obtained $\dot{V}O_{2max}$ mean values in breath-by-breath and average of 5, 10, 15, 20 and 30 s sampling intervals, between ~49 and 53 ml.min^{-1}.kg^{-1}, were similar to those described in the literature for front crawl experienced male competitive swimmers [6, 16, 22, 29, 32, 33], and lower than elite male swimmers [11, 21, 34, 35]. The values of blood lactate concentration (between 8.0 and 12.7 mmol.l^{-1}), respiratory exchange ratio (from 1.11 to 1.17), and heart rate (between 181 and 207 b.min^{-1}), correspond to the step in which $\dot{V}O_{2max}$ was obtained by meeting the previously described criteria [17], and are also in accordance with the specialized literature [6, 10, 12, 16, 21, 22, 29, 32, 33].

The primary aim of this study was to propose a judicious $\dot{V}O_{2max}$ time-averaging method that allows better identifying the incidence of the $\dot{V}O_2$ plateau in swimming. Some laboratory studies were conducted previously, trying to verify the methodological factors that may affect the $\dot{V}O_2$ kinetics, once it is well known that the manipulation of the sampling intervals may result in substantial $\dot{V}O_2$ differences during incremental exercise testing [2, 15, 24, 26]. Our average results seem to corroborate these studies conducted in treadmill running and cycle ergometry, evidencing that lower sampling interval frequencies underestimate the $\dot{V}O_{2max}$ values; although the current study included only 11 swimmers, this fact was observed particularly for the 20 and 30 s averaging comparing to breath-by-breath data, independent of the step length used in the incremental protocol. This was mathematically expected due to the greater temporal resolution that breath-by-breath sampling interval offers, allowing a better examination of small changes in $\dot{V}O_2$ when performing at high intensities. However, the breath-by-breath gas acquisition could induce a significant $\dot{V}O_2$ variability [25], leaving the most appropriate sampling interval still unresolved. This is why some authors [15] underlined the importance of analysing the impact of inter-breath variability in gas exchange, which might not represent the variations in oxygen loading in the lung or its utilization in the exercising muscles. According to the obtained results, the 5, 10 and 15 s time averages seem to be the best to use as a standard $\dot{V}O_{2max}$ time-averaging method, corroborating the literature for ergometer exercise [1, 2, 25]. As the 10 s sampling interval obtained the highest incidence of the $\dot{V}O_2$ plateau, independent of the step lengths used, we suggest its use when assessing $\dot{V}O_{2max}$ in swimming. However, it is important to highlight that some authors, studying other sports than swimming, did not use time average intervals to assess $\dot{V}O_2$ kinetics but the mean of 3, 5 or 10 breaths [15]. Thus, future studies should have this in mind, and also try to increase the number of subjects tested.

In addition, the percentage of $\dot{V}O_{2max}$ occurrence in protocols with 200, 300 and 400-m step lengths was examined. Traditionally, $\dot{V}O_{2max}$ (or $\dot{V}O_{2peak}$) assessment protocols in swimming use steps ≥ 4 min [16, 30, 31, 37], which, according to some authors [32, 37], is necessary to cause a temperature increase and a pH decrease in the muscle, fostering an environment which is optimal for oxygen extraction. As the longer steps are more likely to produce a physiological steady state [28, 30], it was hypothesized that the 400-m steps implied a higher incidence of plateau in $\dot{V}O_2$ at $\dot{V}O_{2max}$; however, independent of the time average used, it was observed that the 400-m step never accounted for a higher percentage of occurrence of plateau at $\dot{V}O_{2max}$ than the other step lengths; the 200 and 300-m steps accounted for a similar percentage of $\dot{V}O_2$ plateau incidence, with higher percentages in the breath-by-breath and 10 and 20 s sampling intervals for the 300-m compared to the 200-m step protocol.

Lastly, the 400-m step protocol presented lower $\dot{V}O_{2max}$ values, compared to the 200 and 300-m step lengths, whatever time-average intervals were used (with exception of the 10 s sampling interval, in which no differences were observed). Obtaining lower mean peak $\dot{V}O_2$ in protocols with 6 min duration compared to 1 min steps, Kuipers et al. [20] warned that incremental exercise protocols with relatively long duration of each step may prevent achievement of peak values of $\dot{V}O_2$ and heart rate because of premature fatigue. In fact, 200 and 300-m step lengths were used in some recent studies that implemented intermittent incremental swimming protocols for $\dot{V}O_{2max}$ assessment [11, 19, 22, 28, 29, 31, 33], as well as in not so recent ones [38]; in addition, a previous comparison between 200, 300 and 400-m step protocols and a maximal lactate steady state test concluded that the use of 200 and 300-m step lengths are valid for individual anaerobic threshold assessment, and that the 400-m step distance underestimates the blood lactate concentrations corresponding to that parameter [12]. Despite the low number of swimmers in the current study, the above-mentioned facts suggest that 200 and 300-m step lengths could be used instead of 400-m steps, both for $\dot{V}O_{2max}$ and anaerobic threshold assessment. Furthermore, the shorter 200-m steps are more specific to the training and competitive requirements of swimmers [28, 35], and the use of this step distance for $\dot{V}O_{2max}$ assessment in swimming represents a compromise between a metabolic steady state and swimming velocities more specific to competition.

Conclusions

The results of this study indicate that shorter sampling intervals (≤ 15 s) allowed the highest incidence of the $\dot{V}O_2$ plateau, independent of the step lengths used, and that the 200 and 300-m step protocols accounted for higher percentage of $\dot{V}O_2$ plateau incidence, and higher $\dot{V}O_{2max}$ values, compared to the 400-m step protocol. As an optimal sampling interval should be used, and considering that swimmers and coaches prefer testing programs where the swimming distance is not long (easier to integrate in their workout schedule), the use of the 10 s time-average interval in an 200-m step incremental protocol is proposed for $\dot{V}O_{2max}$ assessment in swimming. It is suggested, for future studies conducted in larger samples, to test if the 10 s time-average interval is the best to use in an incremental test with 200-m steps, as it is known that distinct exercise intensities (moderate, heavy and severe) imply different $\dot{V}O_{2max}$ kinetics.

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