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Validity of Postexercise Measurements to Estimate Peak VO_2 in 200-m and 400-m Maximal Swims

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ABSTRACT

To assess the validity of postexercise measurements to estimate oxygen uptake ($\dot{V}O_2$) during swimming, we compared $\dot{V}O_2$ measured directly during an all-out 200-m swim with measurements estimated during 200-m and 400-m maximal tests using several methods, including a recent heart rate (HR)/$\dot{V}O_2$ modelling procedure. 25 elite swimmers performed a 200-m maximal swim where $\dot{V}O_2$ was measured using a swimming snorkel connected to a gas analyzer. The criterion variable was $\dot{V}O_2$ in the last 20 s of effort, which was compared with the following $\dot{V}O_{2peak}$ estimates: 1) first 20-s average; 2) linear backward extrapolation (BE) of the first 20 and 30 s, 3 × 20-s, 4 × 20-s, and 3 × 20-s or 4 × 20-s averages; 3) semilogarithmic BE at the same intervals; and 4) predicted $\dot{V}O_{2peak}$ using mathematical modelling of 0–20 s and 5–20 s during recovery. In 2 series of experiments, both of the HR/$\dot{V}O_2$ modelled values most accurately predicted the $\dot{V}O_{2peak}$ (mean Δ = 0.1–1.6 %). The BE methods overestimated the criterion values by 4–14 %, and the single 20-s measurement technique yielded an underestimation of 3.4 %. Our results confirm that the HR/$\dot{V}O_2$ modelling technique, used over a maximal 200-m or 400-m swim, is a valid and accurate procedure for assessing cardiorespiratory and metabolic fitness in competitive swimmers.

Introduction

Competitive swimming performance depends on the swimmer's maximal metabolic power (aerobic and anaerobic energy sources) and the energy cost to swim a unit distance [10, 47]. Hence, the maximal oxygen uptake ($\dot{V}O_{2max}$) is considered to be an important performance factor as an expression of maximal aerobic power. Traditionally, incremental tests have been mostly used to test $\dot{V}O_{2max}$ in swimmers (see [41] for a review). Few studies have assessed oxygen uptake ($\dot{V}O_2$) in elite swimmers in pool conditions within the range of race speeds and times. The peak oxygen uptake ($\dot{V}O_{2peak}$) was shown to be very closely related to performance at 100 m ($r^2 = 0.62$) and 400 m ($r^2 = 0.56$) [34], and at 365.8 m ($r^2 = 0.36$) [7] distances among competitive swimmers. Other authors did not find such a relationship [28]. The amplitude and time delay of the principal component of $\dot{V}O_2$ combined were found to explain 46 % of the variance of the 100-m performance [36].

However, the question of whether $\dot{V}O_{2max}$ can be attained during a maximal incremental and/or all-out swimming test is controversial. In his pioneering work, Holmér compared the $\dot{V}O_{2peak}$ measured using the Douglas bag method in the swimming flume, treadmill running and cycling and found a higher $\dot{V}O_{2peak}$ in running than in swimming [15]. Some years later, using breath-by-breath (bxb) technology during recovery, Rodríguez did not find differences in $\dot{V}O_{2peak}$ between a 400-m maximal swim and incremental laboratory cycling and running tests [32]. The later results were attributed to very fast $\dot{V}O_2$ on-kinetics in competitive swimmers [34, 39, 43]. This issue needs to be clarified at least in relation to what can be called the "swim-specific" $\dot{V}O_{2max}$ determination, defined as the maximal $\dot{V}O_2$ attainable during supramaximal swimming.

From a technical standpoint, bxb $\dot{V}O_2$ measurements during swimming require the use of special respiratory equipment (e. g., waterproof breathing valves, swimming snorkels and assembly tubing) connected to open circuit gas analyzers [1, 21, 35, 41]. However, the use of such equipment changes the swimmer's technique and hydrodynamics, resulting in lower swimming speeds [2, 20, 23]. Estimating $\dot{V}O_2$ from postexercise measurements (i. e., gas collection after swimming only) seems to be a plausible alternative provided that the error of estimation is sufficiently low. Di Prampero et al. [8] were the first to use postexercise $\dot{V}O_2$ measurements to determine $\dot{V}O_2$ at a submaximal steady state by fitting an exponential least squares regression to time zero (t_0) of the $\dot{V}O_2$ recovery phase (i. e., backward extrapolation [BE]) during the steady-state phase of a submaximal treadmill walking exercise, and they observed no differences between measured and estimated values. Later, Léger et al. validated this BE technique during maximal multistage laboratory tests (cycle ergometer and running) and field running by comparing the $\dot{V}O_{2peak}$ during exercise with BE estimates from recovery measures [24].

In swimming, the BE technique was first applied and validated in multistage continuous free swimming and treadmill running tests using the Douglas bag technique by Montpetit et al. [25], who found that the measured and estimated $\dot{V}O_{2peak}$ values were well correlated and the standard error of estimation (SE_E) was low (3.7 %). Since then, this technique has often been used for estimating $\dot{V}O_2$ during swimming [7, 17, 23, 28, 44, 46, 48, 49] and is now considered a mainstream procedure by several leading research groups. However, Montpetit et al. suggested that the validity of the BE technique in swimming is restricted to continuous and progressive exercise to exhaustion (but not of supramaximal intensity) longer than 4–5 min, with no substantial delay in gas collection after the cessation of exercise [25]. In this sense, previous studies conducted with the Douglas bag technique reported a time delay of 12–35 s at the onset of the $\dot{V}O_2$ recovery curve after supramaximal exercise [9, 19, 29]. Recent studies using bxb measurements confirmed the existence of a delay of ~ 3–14 s [4, 42]. This delay at the onset of the $\dot{V}O_2$ recovery curve is likely the cause of the overestimation (20 %) described by Lavoie et al. after a supramaximal 400-m swim when $\dot{V}O_{2peak}$ was estimated by BE using postexercise Douglas bag measurements [23]. In a recent study published using bxb equipment, we found that linear and semilogarithmic BE at different time intervals systematically overestimated the $\dot{V}O_{2peak}$ measured during a 200-m supramaximal swim by 3.5–17.9 % [4].

To circumvent this problem, Lavoie et al. proposed that a simplified procedure based on a single 20-s postexercise Douglas bag gas collection upon recovery is a good and practical indicator of $\dot{V}O_{2peak}$ in swimming [23]. 2 years later, the simplified procedure was adopted by Costill et al., and they reported a high correlation with the $\dot{V}O_{2peak}$ measured during 7 min of tethered breaststroke swimming, though they also observed a small decline in $\dot{V}O_2$ during the first 20 s that yielded a ~ 6 % underestimation of the measured values. We recently obtained similar results using bxb measurements and observed a significant underestimation of − 3.3 % [5] and − 4.5 % [4] of the measured values when $\dot{V}O_{2peak}$ was estimated from a single postexercise average (i. e., 20-s mean of bxb values).

Recently, our group designed and evaluated a new modelling procedure based on heart rate (HR) and postexercise $\dot{V}O_2$ measurements for estimating $\dot{V}O_{2peak}$ at the end of an all-out swimming test [5]. The estimated values calculated on the first 20 s upon recovery (t_0–t_{20}) showed almost identical results (mean Δ = 0.5 %) and a low SE_E (3.8 %) compared with the exercise $\dot{V}O_{2peak}$ measured bxb during the same 200-m supramaximal swim; similar results were obtained (mean Δ = 1.1 %; SE_E = 4.1 %) when the new method was applied to 20-s postexercise data that discarded the first 5 s of recovery (t_5–t_{20}) [4]. Hence, this new modelling procedure has been shown to be the most accurate procedure for estimating $\dot{V}O_{2peak}$ and overcomes the bias incurred by other methods. However, previous research is limited to 200-m supramaximal swimming and involved continuous $\dot{V}O_2$ measurements during exercise and recovery, that is, without a time lag in gas collection between the periods. The question persists as to whether the time-variant delay in obtaining the first breaths upon recovery after free swimming can affect the validity and precision of the estimation.

Therefore, we aimed: 1) to assess the validity of postexercise $\dot{V}O_2$ measurements in estimating $\dot{V}O_{2peak}$ by comparing $\dot{V}O_2$ measured directly using a swimming snorkel connected to a bxb gas analyzer with that estimated by commonly used postexercise estimation techniques; 2) to test the hypothesis that 200- and 400-m supramaximal swimming tests are equally valid for assessing swim-specific $\dot{V}O_{2max}$ among competitive swimmers.

Methods

Participants

In series A, 8 elite female swimmers were recruited as subjects via their national and/or Olympic teams. In series B, 17 elite swimmers, also members of their national and/or Olympic teams, consisting of 12 females and 5 males (▶ **Table 1**), volunteered to participate. Selection criteria were to have competed internationally during the previous season and/or being pre-selected as a member of their National and/or Olympic teams. Specific exclusion criteria included recent illness or injuries preventing normal training and racing. The FINA Point Scoring (FPS) system was used to quantify their competitive level, and a point score (range 0–1 100) was ascribed to each swimmer according to her/his best time in her/his main event, scaled up or down from 1 000 points based on the fastest global yearly performance in each event (▶ **Table 1**).

All swimmers were fully informed about the study, which adhered to the IJSM's ethical standards [14], and provided written informed consent to participate; this study received approval from the Ethics Committee for Clinical Sport Research of Catalonia.

Testing

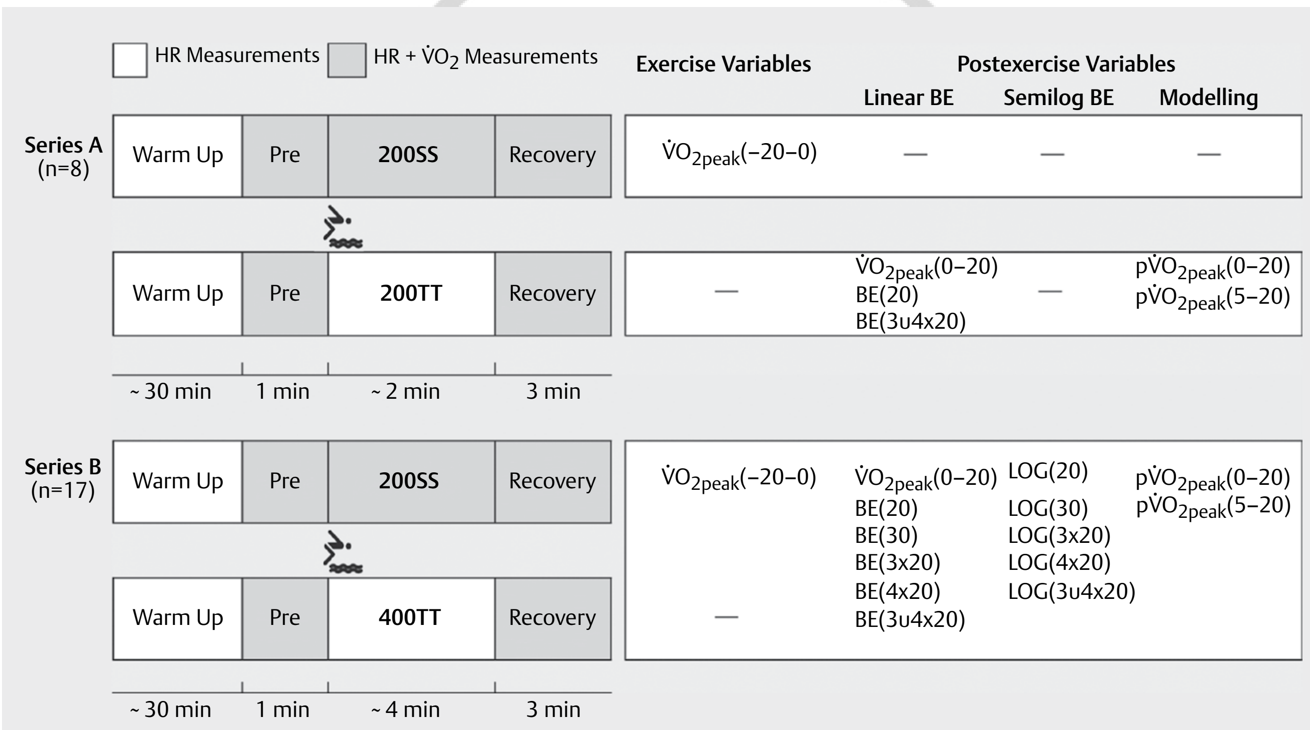
All testing was conducted in a 50-m indoor pool (water temperature was 26–27 °C, and air temperature was 27–28 °C). ▶ **Fig. 1** summarizes the data collection procedures and the derived variables used for analysis of both series A and B.

In the first testing session, after a competition warm-up (~30 min), the subjects rested outside the water while the respiratory equipment was calibrated and set up. Then, the swimmers performed an all-out 200-m front crawl swim using a swimming snorkel (200SS). During the test, an assistant walked at the edge of the pool, keeping pace with the swimmer while carrying the respiratory equipment on a pole. Following the exercise, the swimmers remained in the water for 3 min in an upright position and immersed to the mid-sternum.

▶ **Table 1** Subjects' characteristics and 200/400-m swimming performance.

	Series A (n = 8)	Series B (n = 17)		
	Females	**Females (n = 12)**	**Males (n = 5)**	**All (n = 17)**
Age (years)	19.3 ± 2.3	19.7 ± 4.2	22.1 ± 2.6	20.4 ± 3.9
Height (cm)	175.4 ± 6.1	171.6 ± 5.2	182.6 ± 3.3	174.9 ± 6.9
Body mass (kg)	65.8 ± 5.4	62.3 ± 6.2	76.0 ± 5.7	66.3 ± 8.7
FPS *	806 ± 64	840 ± 63	810 ± 43	832 ± 58
Time 200/400 m (s)	134.1 ± 3.9	283.3 ± 9.4	265.6 ± 9.3	278.1 ± 12.3
Mean velocity 200 m ($m \cdot s^{-1}$)	1.492 ± 0.043	1.413 ± 0.045	1.507 ± 0.052	1.441 ± 0.064

Values are mean ± SD; * FPS: FINA Point Scores



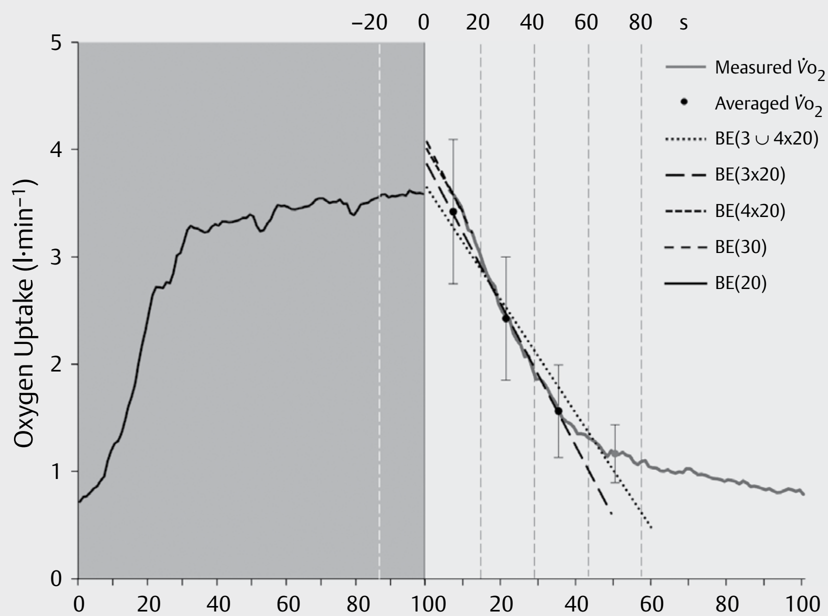
▶ **Fig. 1** Schematic of the experimental procedures for series A and B. In the timeline blocks, grey shadowed areas denote continuous $\dot{V}O_2$ and heart rate measurements, whereas white areas denote heart rate measurements only ($\dot{V}O_2$ was measured during the recovery period only). See the text for details.

In series A, during a second session taking place at least 24 h after the first, the swimmers performed a front-crawl 200-m time trial (200TT) with the front crawl stroke with a block start and with no companions in the same lane or either one next to it. A competition-like start was used, and the swimmers were instructed to achieve the best time possible. Time was manually recorded to the nearest 0.01 s by 3 experienced timers, and the median values were used for analysis. In series B, following the same general procedure as in series A, the swimmers performed a 400-m all-out test with the front crawl stroke (400TT).

Data collection and processing

In the 200SS tests, $\dot{V}O_2$ was continuously measured bxb using a telemetric portable gas analyzer (K4 b², Cosmed, Italy) connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system, which has been previously validated [21, 35]. Pulmonary gas exchange was measured 1 min before, during the maximal swim, and 3 min after exercise. HR was continuously measured using beat-by-beat monitors (CardioSwim, Freelap, Switzerland). $\dot{V}O_2$ and HR data were time-aligned to the start of the measurements, 1-s interpolated, and plotted against time.

The swimmers performed the 200TT and 400TT tests without the respiratory equipment, i. e., swimming completely unrestricted (▶ **Fig. 1**). $\dot{V}O_2$ was collected using an oronasal Hans-Rudolph 7 400 mask (Hans Rudolph Inc., Shawnee, Kansas, USA), 1 min before and for 3 min immediately after exercise cessation while the subject rested in the water in an upright position immersed to the mid-sternum. The mask was firmly applied immediately after the swim with care to avoid leakage and to minimize the time before the first respiratory data were obtained. The swimmers were instructed about the proper technique before the swims. The interchangeability of the swimming snorkel and the oronasal mask used



▶ **Fig. 2** Schematic diagram of $\dot{V}O_2$ (continuous line, 1-s averaged values for the entire group of swimmers) measured during exercise (black line, dark shadowed area) and recovery (grey line) during a 200-m all-out swim. The double x-axis represents the percentage of exercise and recovery total time. The lighter grey area represents the time delay of postexercise $\dot{V}O_2$ measurements. Discontinuous vertical lines illustrate time limits (s) in which $\dot{V}O_2$ values were averaged (black dots, mean ± *SD*) or where regression was applied. The regression lines projected on the t_0 of recovery were used to estimate $\dot{V}O_{2peak}$ using the various BE procedures. See the text for definitions and details.

in this study was previously established [21]. HR was continuously monitored as in the previous tests.

Measured $\dot{V}O_{2peak}$ during exercise

$\dot{V}O_{2peak}$ during exercise was taken as the averaged values measured within the last 20 s of exercise (t_{-20}–t_0), referred to as $\dot{V}O_{2peak}$ (−20–0), and taken as the criterion value for all comparisons. 2 previous studies showed that $\dot{V}O_{2peak}$(−20–0) did not differ from $\dot{V}O_{2peak}$ calculated by fitting the 1-s interpolated bxb data to a nonlinear least-square regression using a biphasic $\dot{V}O_{2peak}$ kinetics model [5, 33]. The reliability of $\dot{V}O_{2peak}$ measurements using this procedure are characterized by a typical error of 3.1 % (95 % CI: 1.1–5.1 %; n = 9) [33].

Estimated $\dot{V}O_{2peak}$ from postexercise measurements

As in a previous study [4], the following 3 techniques were used to estimate $\dot{V}O_{2peak}$ from HR and/or $\dot{V}O_2$ kinetics during recovery: 1) linear BE, 2) semilogarithmic BE, and 3) HR/$\dot{V}O_2$ modelling procedures. ▶ **Fig. 2** shows the averaged $\dot{V}O_2$ values measured during the all-out 200-m swims (200SS) and during recovery (200TT, 400TT) and schematizes the calculation procedure by the various BE techniques.

▶ **Fig. 1,2** summarize which variables were analyzed in each experimental series, but for the sake of order, we will define their groups here. First, the following 6 procedures were used in the BE technique: 1) $\dot{V}O_{2peak}$ (0–20) – average values measured within the first 20 s of recovery ($t_0 - t_{20}$); 2) BE(20) – estimated value calculated by BE to the t_0 of the first 20-s values of the $\dot{V}O_2$ recovery curve; 3) BE(30) – estimated $\dot{V}O_{2peak}$ by BE to the t_0 of the first 30-s values of the $\dot{V}O_2$ recovery curve; 4) BE(3 × 20) – BE value calculated from the first three 20-s average values of the $\dot{V}O_{2peak}$ recovery curve; 5) BE(4 × 20) – BE value calculated from the first four 20-s average values of the $\dot{V}O_2$ recovery curve; and 6) BE(3∪4 × 20) – estimated value calculated by BE to the t_0 of the best regression fit (3 × 20 s or 4 × 20 s) of the $\dot{V}O_2$ recovery curve.

Second, the same estimations were performed using a semilogarithmic procedure (LOG), i. e., the logarithms of the measured $\dot{V}O_2$ values were plotted as a function of the recovery time and backward extrapolated to t_0, as in the original paper by Léger et al. [24]. Using analogous notation, the following 5 calculations were computed to estimate $\dot{V}O_{2peak}$: 1) LOG(20); 2) LOG(30); 3) LOG(3 × 20); 4) LOG(4 × 20); and 5) LOG(3∪4 × 20).

Third, $\dot{V}O_{2peak}$ was estimated using a HR/$\dot{V}O_2$ modelling technique, where p$\dot{V}O_2$ (0–20) is the 20-s averaged values of the predicted $\dot{V}O_2$ based on the HR and $\dot{V}O_2$ kinetics according to the procedure described elsewhere [5]. In short, based on Fick's principle, the model calculates a predicted $\dot{V}O_2$ at a given time of recovery (t) using changes in HR as a proxy for changes in cardiac output and the oxygen pulse as a proxy for the arterio-venous O_2 difference according to the equation:

$$p\dot{V}O_2(t) = \dot{V}O_2(t) \cdot HR_{end-exercise}/HR(t) \quad \text{(Eq. 1)}$$

where $p\dot{V}O_2(t)$ is the predicted (modelled) $\dot{V}O_2$ at time t; $\dot{V}O_2(t)$ is the postexercise 1-s interpolated $\dot{V}O_2$ at time t; HR(t) is the postexercise 1-s interpolated HR value at time t; and $HR_{end\text{-}exercise}$ is the

▶ **Table 2** Series A. Peak $\dot{V}O_2$ measured during a 200-m all-out swim (200SS) and estimated from postexercise measurements after an unimpeded 200-m all-out swim (200TT) using various calculation procedures (n = 8).

Technique	Procedure	Peak $\dot{V}O_2$	95 % CI		Mean difference		r^2	SE_E		Diff. from criterion[#]
		(ml·min⁻¹)	(ml·min⁻¹)		(ml·min⁻¹)	(%)		(ml·min⁻¹)	(%)	(p)
Exercise (criterion)	$\dot{V}O_{2peak}(-20–0)$	3 187 ± 530	2 744	3 630	–	–	–	–	–	–
Linear BE	$\dot{V}O_{2peak}(0–20)$	3 084 ± 518	2 650	3 517	− 104	− 3.4	0.787	264	8.3	1.000
	BE(20)	3 676 ± 607	3 168	4 184	489	13.3	0.639	344	10.8	0.106
	BE(3≤4 × 20)	3 448 ± 598	2 949	3 948	261	7.6	0.865	211	6.6	0.188
Modelling	$p\dot{V}O_{2peak}(0–20)$	3 240 ± 511	2 812	3 667	53	1.6	0.844	226	7.1	1.000
	$p\dot{V}O_{2peak}(5–20)$	3 229 ± 511	2 802	3 657	42	1.3	0.848	223	7.0	1.000

Values are mean ± *SD*. 95 % CI, 95 % confidence interval; %, percent of criterion value; mean diff., mean difference with criterion value; r^2, Pearson's coefficient of determination; SE_E, standard error of estimate; #, ANOVA RM (post-hoc Bonferroni) compared with the criterion

highest HR value of the last 10 s of exercise; single peaks that were 5 bpm higher than the last 10-s HR average were excluded; this procedure aims to select the highest HR value at the end of the exercise (10 s) while minimizing the noise (aberrant beats) sometimes caused by the intense effort in the water.

The time intervals for each type of procedure were selected from previous investigations [4, 5] in which different intervals between 0 and 80 s were compared to elucidate which ones providing the best exercise $\dot{V}O_{2peak}$ estimates.

Statistical analysis

Descriptive data are expressed as the mean, standard deviation (± SD), and mean difference between the mean values (mean Δ). The normality of the distributions and homogeneity of variance were checked and confirmed with the Shapiro-Wilk and Levene tests, respectively. In series A, one-way analysis of variance with repeated measures (RM-ANOVA) and post-hoc Bonferroni tests, when appropriate, were used for multiple comparisons between exercise (criterion) and postexercise estimates. In series B, 2-way RM-ANOVA and post-hoc Bonferroni tests, when appropriate, were used for multiple comparisons between criterion and estimated $\dot{V}O_{2peak}$ values, between $\dot{V}O_{2peak}$ in the 2 tests (200SS vs. 400TT), and for test-by-procedure interaction. The Bonferroni correction for multiple comparisons was used when appropriate. Pearson's coefficient of determination (r^2) was used to assess the relationship between variables and the proportion of shared variance. The criteria adopted to interpret the magnitude of the correlation (computed as r^2 and rounded up) between variables were < 0.01, trivial; > 0.01–0.1, small; > 0.1–0.3, moderate; > 0.3–0.5, large; > 0.5–0.8, very large; and > 0.8–1.0, almost perfect [16]. To determine estimation bias, the mean Δ and standard error of the estimate (SE_E) – both expressed as absolute values and the % of the mean – and the limits of the 95 % confidence interval (95 % CI) were calculated. Differences between measured and estimated $\dot{V}O_{2peak}$ and the level of agreement (mean Δ ± 1.96 SD) were analyzed graphically using Bland-Altman difference plots [3]. Under- and overestimation are defined as the difference between the estimated and criterion mean values, expressed as a percentage of the criterion's mean. The level of significance was set at $p < 0.05$. Statistical analyses were conducted using SPSS 18.0 for Windows.

Results

Series A

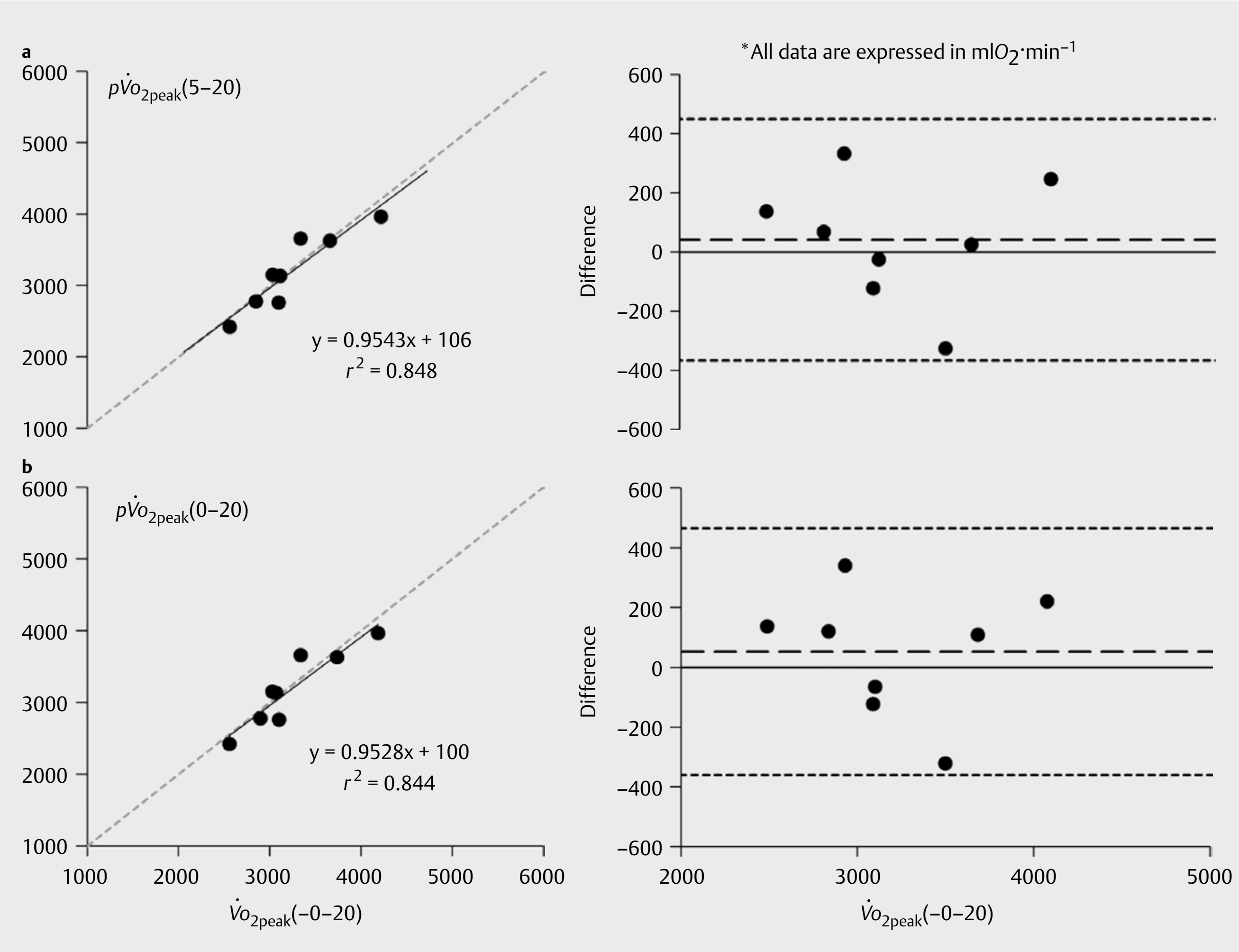
Swimming times were 139.5 ± 4.6 s and 134.1 ± 3.9 s for 200SS and 200TT, respectively. In 200TT, a time gap from t_0 to the first valid $\dot{V}O_2$ measurement of 3.4 ± 1.9 s, and a fast component TD (light grey area in ▶ **Fig. 2**) of 7.6 ± 4.4 s were observed. ▶ **Table 2** compares the criterion of $\dot{V}O_{2peak}$ measured during exercise (200SS) with that estimated using different procedures from postexercise measurements after an unrestricted 200TT swim. None of the estimated values differed from the criterion. However, the best estimates of the criterion values were provided by both modelling procedures, e. g., $p\dot{V}O_{2peak}(5–20)$ and $p\dot{V}O_{2peak}(0–20)$, which showed almost perfect correlation with the criterion values ($r^2 > 0.84$) and the lowest mean differences (mean Δ < 1.6 %) and had a low estimation bias (SE_E = 7 %). Linear BE methods overestimated the criterion values by 7.6–13.3 %, on average, whereas $p\dot{V}O_{2peak}(0–20)$ underestimated the measured values by 3.4 %.

The regression and Bland-Altman plots in ▶ **Fig. 3** also show an almost perfect correlation and a good level of agreement between the 2 modelling procedures, with $\dot{V}O_{2peak}(5–20)$ offering a slightly better predictive capacity (see ▶ **Table 2** for statistics).

Series B

Swimming times were 141.8 ± 10.2 s and 278.1 ± 12.3 s for 200SS and 400TT, respectively. In 200SS, a fast-component TD (light grey area in ▶ **Fig. 2**) of 9.5 ± 4.8 s was noted. In 400TT, there was a time gap from t_0 to the first valid $\dot{V}O_2$ measurement of 2.8 ± 2.4 s, and a fast-component TD of 6.7 ± 4.2 s. ▶ **Table 3** compares the $\dot{V}O_{2peak}$ values measured during 200SS and estimated from postexercise measurements following the same test and the 400TT by various linear BE procedures. Only BE (30) was different from the criterion and between distances. Except for $\dot{V}O_{2peak}(0–20)$, which underestimated the criterion $\dot{V}O_{2peak}$ in 200TT and 400TT by 4.5 % and − 1.3 %, respectively, BE procedures overestimated the criterion at both distances. The lowest mean difference with criterion values (− 1.3 %) was seen when using $\dot{V}O_{2peak}(0–20)$ at 400TT.

As shown in ▶ **Table 4**, the semilogarithmic BE procedures did not differ from the criterion, with the exceptions of LOG (20) in both



▶ **Fig. 3** Series A: Comparison between $\dot{V}O_2$ measured during exercise (200SS) – a criterion $\dot{V}O_{2peak}$ (– 20–0) in the x-axis – and estimated from postexercise measurements after 200TT using the HR/ $\dot{V}O_2$ modelling procedure: **a** $\dot{V}O_{2peak}$ (–5–20) and **b** $\dot{V}O_{2peak}$ (–20–0). The left panel shows the regression line (solid back) and the equality line (dashed grey). In the right panel, the y-axis represents the differences between estimated and measured $\dot{V}O_{2peak}$ values; lines represent equality (solid), mean difference (long-dashed), and ± 95 % limits of agreement (short-dashed). All data are expressed in $mlO_2 \cdot min^{-1}$.

distances and LOG (30) in 200TT only. However, the lowest bias was observed for LOG (20) and LOG (30) at 200TT (mean Δ = 4.7 and 6.1 %, respectively), with the remaining procedures showing exceedingly large differences with the criterion (mean Δ range = 11.0–18.1 %) in both 200TT and 400TT.

No differences were noted between the criterion $\dot{V}O_{2peak}$ values and those estimated using the HR/$\dot{V}O_2$ modelling procedure (▶ **Table 5**), and there was slightly lower bias and better predictive capacity shown by $\dot{V}O_{2peak}(5–20)$, in which the first 5 s after the cessation of exercise were excluded in the estimation (mean Δ = 0.1 and 1.6 % for 200TT and 400TT, respectively). ▶ **Fig. 4** shows the corresponding regression and Bland-Altman difference plots for both variables in 200TT and 400TT.

▶ **Table 6** shows the linear regression equations between the criterion and $\dot{V}O_{2peak}$ estimates for each calculation procedure in both series. These equations can be used to estimate criterion values (x) from values measured using the various estimation procedures (y). See ▶ **Fig. 3–5** for regression statistics.

Discussion

To assess the validity of postexercise measurements to estimate the $\dot{V}O_{2peak}$ after a supramaximal swim, we compared the $\dot{V}O_{2peak}$ values that were measured directly during a 200-m all-out swim (200SS) with those estimated during the same tests and on separate time trials over 200-m and 400-m swims in which the subjects swam completely unrestricted (200TT and 400TT). The main findings were as follows: 1) $\dot{V}O_{2peak}$ can be estimated from postexercise measurements with good accuracy after an all-out middle-distance swim test, even with a time gap between the cessation of exercise and the first $\dot{V}O_2$ measurement; 2) the modelling procedure based on HR and recovery $\dot{V}O_2$ kinetics appears to be the most valid and accurate procedure for estimating $\dot{V}O_{2peak}$ after a maximal swim; and 3) both 200-m and 400-m all-out swims are valid tests for assessing swim-specific $\dot{V}O_2$ when swimmers are fully unrestricted and when the measurements are combined with HR and postexercise $\dot{V}O_2$ measurements.

▶ **Table 3** Series B. Peak $\dot{V}O_2$ measured during a 200-m all-out swim (200SS) and estimated from postexercise measurements following the same test (200SS) and after an unimpeded 400-m all-out swim (400TT) using various linear regression procedures (n = 17).

Procedure	Test	Peak $\dot{V}O_2$	95 % CI		Mean diff.		r^2	SE_E		Diff. with criterion[#]	Diff. between tests[#]
	(m)	(ml · min⁻¹)	(ml · min⁻¹)		(ml · min⁻¹)	(%)		(ml · min⁻¹)	(%)	(p)	(p)
$\dot{V}$O2peak (− 20–0) (criterion)	200	3 192 ± 667	2 850	3 535	–	–	–	–		–	
$\dot{V}$O2peak (0–20)	200	3 055 ± 688	2 701	3 409	− 138	− 4.5	0.878	241	7.5	1.000	0.317
	400	3 152 ± 729	2 778	3 527	− 40	− 1.3	0.778	325	10.2	1.000	
BE(20)	200	3 332 ± 686	2 979	3 685	139	4.2	0.875	244	7.6	1.000	0.077
	400	3 607 ± 829	3 180	4 033	414	11.5	0.446	513	16.1	1.000	
BE(30)	200	3 358 ± 663	3 017	3 699	165	4.9	0.893	225	7.1	0.633	0.007 *
	400	3 706 ± 821	3 284	4 128	513	13.9	0.685	387	12.1	0.028 *	
BE(3 × 20)	200	3 442 ± 766	3 048	3 836	249	7.2	0.850	267	8.4	0.314	0.241
	400	3 573 ± 818	3 152	3 993	380	10.6	0.775	327	10.2	0.093	
BE(4 × 20)	200	3 407 ± 846	2 973	3 842	215	6.3	0.815	296	9.3	1.000	0.786
	400	3 439 ± 828	3 014	3 865	247	7.2	0.809	301	9.4	1.000	
BE(3∪4 × 20)	200	3 438 ± 795	3 029	3 846	245	7.1	0.846	270	8.5	0.533	0.356
	400	3 547 ± 824	3 123	3 971	355	10.0	0.754	341	10.7	0.341	

Values are mean ± *SD*. 95 % CI, 95 % confidence interval; %, percent of criterion value; mean diff., mean difference with criterion value; r^2, Pearson's coefficient of determination; SE_E, standard error of estimate; [#], ANOVA RM (post-hoc Bonferroni); * Significantly different (p < 0.05)

▶ **Table 4** Series B. Peak $\dot{V}O_2$ measured during a 200-m all-out swim (200SS) and estimated from postexercise measurements following the same test (200SS) and after an unimpeded 400-m all-out swim (400TT) using various semilogarithmic backward extrapolation calculation procedures (n = 17).

Procedure	Test	Peak $\dot{V}O_2$	95 % CI		Mean diff.		r^2	SE_E		Diff. with criterion[#]	Diff. between tests[#]
	(m)	(ml · min⁻¹)	(ml · min⁻¹)		(ml · min⁻¹)	(%)		(ml · min⁻¹)	(%)	(p)	(p)
$\dot{V}$O2peak (− 20–0) (criterion)	200	3 192 ± 667	2 850	3 535	–	–	–	–		–	
LOG(20)	200	3 350 ± 695	2 992	3 707	157	4.7	0.879	239	7.5	1.000	0.125
	400	3 588 ± 824	3 165	4 012	396	11.0	0.404	532	16.7	1.000	
LOG(30)	200	3 398 ± 655	3 061	3 735	206	6.1	0.883	235	7.4	0.179	0.010 *
	400	3 748 ± 845	3 313	4 183	556	14.8	0.651	407	12.7	0.028 *	
LOG(3 × 20)	200	3 707 ± 788	3 302	4 112	514	13.9	0.782	321	10.1	0.003 *	0.467
	400	3 808 ± 885	3 353	4 262	615	16,2	0.671	395	12.4	0.013 *	
LOG(4 × 20)	200	3 900 ± 965	3 403	4 396	707	18.1	0.739	352	11.0	0.004 *	0.300
	400	3 717 ± 930	3 239	4 196	525	14.1	0.738	352	11.0	0.042 *	
LOG(3<4 × 20)	200	3 814 ± 899	3 352	4 277	622	16.3	0.759	338	10.6	0.004 *	0.890
	400	3 836 ± 890	3 378	4 293	643	16,8	0.680	389	12.2	0.008 *	

Values are mean ± *SD*. 95 % CI, 95 % confidence interval; %, percent of criterion value; Mean diff., mean difference with criterion value; r^2, Pearson's coefficient of determination; SE_E, standard error of estimate; [#], ANOVA RM (post-hoc Bonferroni); * Significantly different (p < 0.05)

In-water $\dot{V}O_2$ direct measurement requires breathing through a swimming snorkel connected with a system of tubes and built-in valves that allows collecting the expired gases while keeping dry the inspiratory and expiratory tubes and the analyzers. To enable continuous measurements in the pool, portable gas analyzers are now preferred by many investigators because of their more advantageous sampling capability, practicality, and acceptable level of accuracy [41]. This methodology is certainly a requirement when continuous measurements are needed during exercise (e. g., $\dot{V}O_2$ kinetics analysis, cardiorespiratory response during exercise). However, even if these constraints do not prevent the investigation of many aspects of the physiological response during swimming (see [41] for a review), the measurement of the respiratory function during exercise does restrict the full expression of performance capacity in pool conditions, particularly during maximal swimming. For instance, the speed attained in all-out 100-m [2] or 400-m tests [23] is faster when the swimmer swims unconstrained (~13–16 % and ~5–6 %, respectively). During multistage continuous tests, mean differences of ~10 % in maximal speed [20] and in maximal speed at $\dot{V}O_{2max}$ [25] have been reported. In fact, the use of swim-

▶ **Table 5** Series B. Peak $\dot{V}O_2$ measured during exercise (200SS) and estimated from postexercise measurements by the HR/ modelling procedure following the same test (SS200) and after a 400-m unimpeded swim (TT400).

Procedure	Test	Peak $\dot{V}O_2$	95 % CI		Mean diff.		r^2	SE_E		Diff. with criterion[#]	Diff. between tests[#]
	(m)	(ml · min⁻¹)	(ml · min⁻¹)		(ml · min⁻¹)	(%)		(ml · min⁻¹)	(%)	(p)	(p)
$\dot{V}$O2peak (−20–0) (criterion)	200	3 192 ± 667	2 850	3 535	–	–	–	–		–	
p$\dot{V}$O2peak (0–20)	200	3 217 ± 691	2 861	3 572	24	0.7	0.861	257	8.0	1.000	0.373
	400	3 303 ± 694	2 946	3 659	110	3.3	0.747	346	10.9	1.000	
p$\dot{V}$O2peak (5–20)	200	3 194 ± 706	2 831	3 557	2	0.1	0.809	301	9.4	1.000	0.620
	400	3 245 ± 651	2 911	3 580	53	1.6	0.775	327	10.2	1.000	

Values are mean ± *SD*. 95 % CI, 95 % confidence interval; %, percent of criterion value; Mean diff., mean difference with criterion value; r^2, Pearson's coefficient of determination; SE_E, standard error of estimate; #, ANOVA RM (post-hoc Bonferroni)

ming snorkels might alter stroke kinematics [2, 20], swimming technique (e. g., by reducing body rolling), and breathing patterns, and they make it impossible to perform diving starts and flip turns [18, 22], which result in lower swimming speeds. Therefore, estimating the $\dot{V}O_{2peak}$ using postexercise measurements, which enables the swimmers to perform completely unrestricted (i. e., without mouthpiece, snorkel, and tubing), is a clear advantage for pool testing and research, provided that $\dot{V}O_2$ can be estimated with sufficient accuracy.

Series A

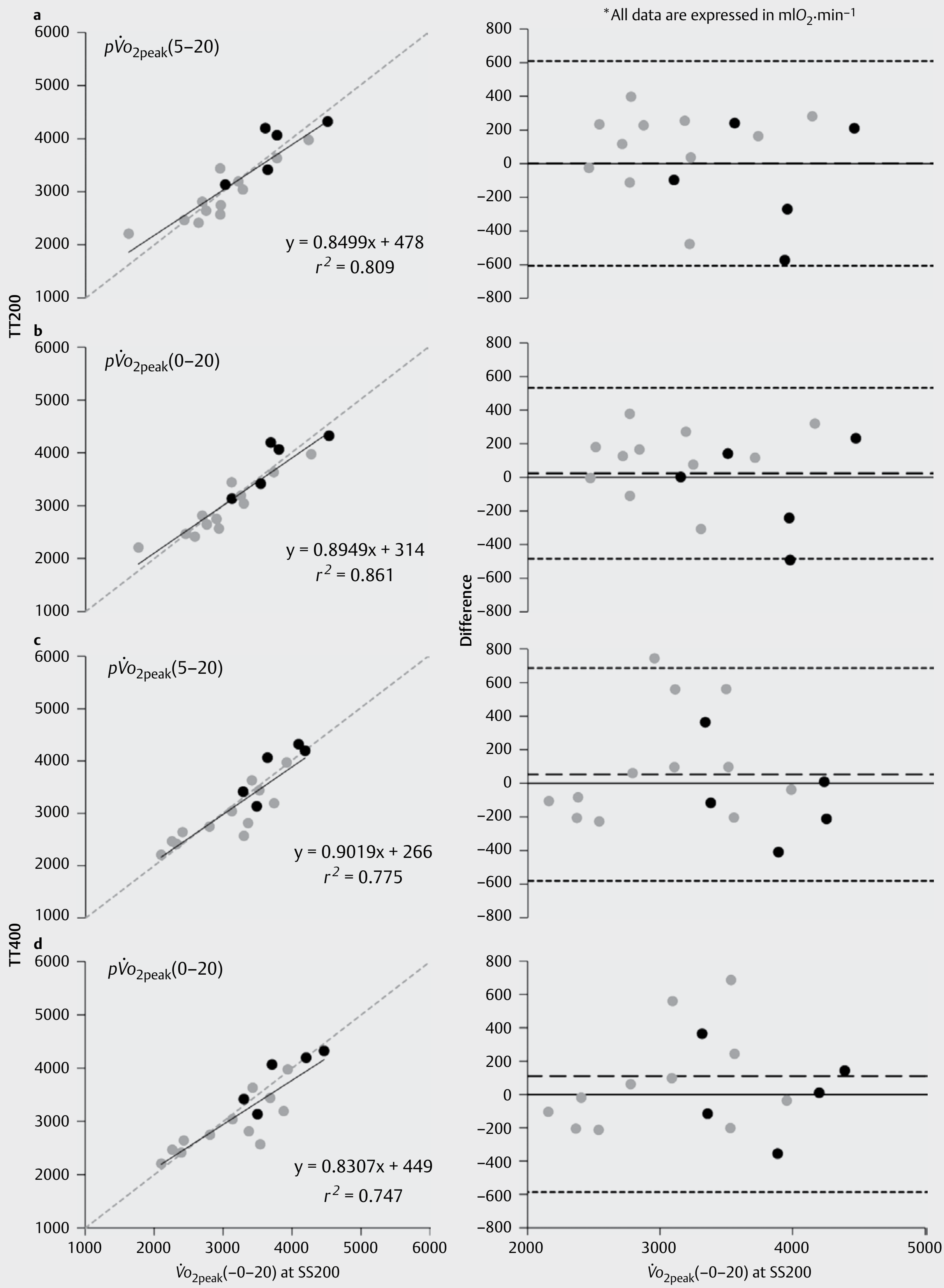
In these experiments, $\dot{V}O_2$ was first measured during exercise and recovery in a maximum 200-m test (200SS) and then compared with postexercise measurements obtained after a separate test over the same distance (200TT) (▶ **Fig. 1**). Thus, in the 200TT test, there was a time-variable gap between the end of the exercise and the start of $\dot{V}O_2$ bxb measurements (3.4 ± 1.9 s). The present results confirm our previous observations in which $\dot{V}O_2$ was measured uninterruptedly [4, 5], showing that the new HR/$\dot{V}O_2$ modelling technique most accurately predicts $\dot{V}O_{2peak}$ regardless of whether the calculation is made using the first 0–20 s or the 5–20 s after the end of the exercise (mean Δ < 1.6 %, similar to 1.1 % in [4]) (▶ **Table 2**, ▶ **Fig. 3**). Conversely, the linear BE methods largely overestimated the criterion values by 7.6–13.3 % (7.6 % and 2.4 % in [4]). The classical single 20-s measurement technique, instead, underestimated the criterion values by 3.4 %; an even larger underestimation was reported by Lavoie et al. in relation to a 400-m supramaximal swim (− 7.7 %) [23] and by Costill et al. in relation to a 7-min tethered breaststroke swim (− 6 %) [7], both of whom used the Douglas bag technique instead of the bxb measurements used in our studies. This series of experiments shows that the time gap occurring between the end of the exercise and the start of bxb gas measurement does not affect the validity and accuracy of postexercise $\dot{V}O_{2peak}$ estimations. Additionally, it supports the validity and accuracy of the new HR/$\dot{V}O_2$ modelling technique.

Series B

Although 200-m maximum swims have been consistently adopted in studies that test competitive swimmers [4, 5, 11, 12, 27, 33, 39, 40], for reasons discussed below, other authors have used longer distances or longer durations (i. e., 400 m, 5–7 min) for assessing $\dot{V}O_{2max}$ in swimmers [7, 23, 31, 32]. Therefore, in the second series of experiments, $\dot{V}O_2$ was first measured during exercise and recovery at 200SS, and then, $\dot{V}O_{2peak}$ was compared with postexercise measurements obtained after a separate 400TT test (▶ **Fig. 1**), in which a time gap also existed between the end of the exercise and the first $\dot{V}O_2$ bxb measurements (2.8 ± 2.4 s).

As in series A, the HR/$\dot{V}O_2$ modelling technique was the best predictor of $\dot{V}O_{2peak}$ (▶ **Table 5**, ▶ **Fig. 4**), notably when the calculation was made using the first 5–20 s after the end of the exercise (mean Δ 0.1 % and 1.6 % for 200TT and 400TT, respectively), which is very similar to series A for 200TT (mean Δ = 1.3 %) and to our previous results for the same distance (mean Δ = 1.1 %) [4]. Only the classical single 20-s measurement procedure (i. e., $\dot{V}O_{2peak}$ estimated from a single 20-s average at immediate recovery) showed comparable results, though only for 400TT, which underestimated the criterion values by − 1.3 %; however, the underestimation increased to up to − 4.5 % during the 200TT, which is similar to the − 3.3 % and − 4.5 % bias observed for a 200-m test in our 2 previous studies [4, 5].

The BE techniques (i. e., extrapolation to t_o of the recovery of average values obtained during 60–80 s) all yielded a larger bias both for the 200TT (mean Δ range = 4.2 –7.2 %) and 400TT (mean Δ range = 7.2 % to 13.9 %) tests (▶ **Table 3**), and an even larger bias was observed in the semilogarithmic BE estimations (mean Δ range = 4.7 –18.1 %, and 11.0–16.8 % for 200TT and 400TT tests, respectively), which makes them useless for the estimation of $\dot{V}O_{2peak}$ during swimming. These results closely replicate those of our previous study, which used an identical methodology during a 200SS test in which $\dot{V}O_2$ was measured uninterruptedly [4]; they are also consistent with the large overestimation (20 %) reported by Lavoie et al. during a 400-m maximum test using the Douglas bag technique and semilogarithmic BE calculations that were comparable to LOG(3∪4 × 20) (i. e., linear regression of 3 or 4 20-s bag samples) [23]. This large overestimation is most likely related to a delay at the onset of the $\dot{V}O_2$ recovery curve after supramaximal exercise. This phenomenon was first reported by di Prampero et al., who observed that contrary to steady-state aerobic exercise,



▶ **Fig. 4** Series B. Comparison between the $\dot{V}O_2$ measured during exercise (200SS) – criterion $\dot{V}O_{2peak}$ (− 20–0) in the x-axis – and estimated from postexercise measurements using the HR/ $\dot{V}O_2$ modelling procedure at 200TT (**a, b**) and 400TT (**c, d**). Males (black dots) and females (grey dots) are shown separately. The remaining plot details are the same as those in ▶ **Fig. 3**.

▶ **Table 6** Linear regression between $\dot{V}O_{2peak}(0–20)$ criterion values (y) and those estimated using different procedures (x) for series A and B.

Technique	Procedure	Linear regression series A (n = 8)	Linear regression series B (n = 17)	
		200TT	200SS	400TT
Lineal BE	$\dot{V}O_{2peak}(0–20)$	y = 0.9077x + 388	y = 0.9073x + 421	y = 0.8070x + 649
	BE(20)	y = 0.6977x + 622	y = 0.9086x + 165	y = 0.5368x + 1256
	BE(30)	–	y = 0.9508x − 0.3	y = 0.6721x + 702
	BE(3 × 20)	–	y = 0.8019x + 433	y = 0.7177x + 628
	BE(4 × 20)	–	y = 0.71117x + 768	y = 0.7248x + 700
	BE(3∪4 × 20)	y = 0.8242x + 345	y = 0.7719x + 539	y = 0.7027x + 700
Semilogarithmic BE	LOG(20)	–	y = 0.8991x + 181	y = 0.5144x + 1347
	LOG(30)	–	y = 0.9564x − 58	y = 0.6364x + 807
	LOG(3 × 20)	–	y = 0.7485x + 418	y = 0.6175x + 841
	LOG(4 × 20)	–	y = 0.5948x + 877	y = 0.6158x + 903
	LOG(3∪4 × 20)	–	y = 0.6460x + 729	y = 0.6183x + 821
Modelling	$\dot{V}O_{2peak}(0–20)$	y = 0.9528x + 100	y = 0.8949x + 314	y = 0.8307x + 449
	$\dot{V}O_{2peak}(5–20)$	y = 0.9543x + 106	y = 0.8499x + 478	y = 0.9019x + 266

▶ **Table 3–5** for Pearson coefficient of determination (r^2) and estimation bias (SEE_E)

$\dot{V}O_2$ remains near exercise levels for approximately 12–35 s after cessation of a very short duration (11–51 s) of a supramaximal leg-cycling exercise [9], and this was later corroborated for a 1-min all-out cycling exercise and quantified over 5–10 s [45]. In swimming, Costill et al. provided indirect proof by observing the close correlation between postexercise 20-s average $\dot{V}O_2$ values and the $\dot{V}O_{peak}$ (r^2 = 0.96), with relatively small mean differences (~ 6 %), though the correlation decreased during subsequent recovery periods [7]. Using bxb measurements, we observed a TD after an all-out 100-m swim of ~ 14 s [36] and between 3 and 10 s after a 400-m maximum test [30]. Similar results (~ 11 s) were obtained by Sousa et al. during a square-wave maximal swim at 100 % of $\dot{V}O_{2max}$ using a double-exponential function [42] and by Chaverri et al. during a 200-m supramaximal swim (9.1 ± 4.8 s) [4]. The present results confirm the occurrence of this phenomenon in both distances investigated (series A: TD at 200TT = 7.6 ± 4.4 s; series B: at 200SS = 9.5 ± 4.8 s; at 400TT = 6.7 ± 4.2 s).

Therefore, these findings corroborate that the overestimation observed when BE is used to predict $\dot{V}O_{2peak}$ during supramaximal exercise is caused by the time-variant delay during the immediate recovery, such that: 1) as evidenced in ▶ **Fig. 1** (also observed in [4]), there is a slower rate of decrease of the $\dot{V}O_2$ curve at the onset of the recovery period; 2) the analysis of the accurately timed individual $\dot{V}O_2$ curves allowed to quantify this TD in most swimmers; 3) underestimation of the criterion values was observed when $\dot{V}O_{2peak}$ was calculated using the 20-s sampling averages (i. e., $\dot{V}O_{2peak}(0–20)$), whereas a systematic overestimation was noted for the remaining BE calculation methods; and 4) the largest overestimation was yielded by semilogarithmic BE, which may introduce an error derived from the mathematical transformation of the monoexponential regression of the fast component of the $\dot{V}O_2$ recovery curve in a linear function. As opposed to the BE methods, the HR-$\dot{V}O_2$ modelling technique is based on Fick's principle and predicts $\dot{V}O_2$ during recovery using the HR as a proxy for changes in cardiac output and the oxygen pulse as a proxy for the arteriovenous O_2 difference (see [5] for discussion). This procedure, notably when excluding the first 5 s of recovery, i. e., $\dot{V}O_{2peak}(5–20)$, has been shown to provide the most accurate estimations of exercise $\dot{V}O_{2peak}$ without significant bias; in this study, the mean Δ range = 1.1 % for 200TT [4], 1.3 and 0.1 % (200TT) and 1.6 % (400TT).

Another key issue is which distance is most appropriate for assessing the maximal aerobic power in swimmers and whether $\dot{V}O_{2peak}$ at single-distance supramaximal tests can be considered to be swimmers' true $\dot{V}O_{2max}$. As opposed to multistage incremental tests, e. g., 3–7 × 200 m (see [41] for a review), single-distance all-out tests enable the swimmers to attain race speeds provided they can swim fully unrestricted. To date, 200-m swims have been consistently adopted in studies that test competitive swimmers [4, 5, 11, 12, 27, 33, 39, 40] because of the intense activation of both the aerobic and anaerobic energy metabolism [37] and because the duration (~2–2.5 min on average) is sufficient to elicit $\dot{V}O_{2max}$ in most cases [26, 38]. It is possible that shorter or longer distances could limit its attainment, despite the extremely fast $\dot{V}O_2$ kinetics of swimmers, as discussed below. In this study, no differences were noted between $\dot{V}O_{2peak}(5–20)$ at 200TT and 400TT tests (3 194 ± 706 vs. 3 245 ± 651; p = 0.62), suggesting that both distances yield the same $\dot{V}O_{2peak}$ in competitive swimmers.

Concerning the $\dot{V}O_{2peak}$ vs. $\dot{V}O_{2max}$ controversy, which is not restricted to swimming, Holmér compared the $\dot{V}O_{2peak}$ measured using the Douglas bag method in a swimming flume with that obtained during laboratory running and cycling and reported a higher $\dot{V}O_{2peak}$ in running than in swimming; these results were related to the expertise in swimming, as the mean Δ was lower in elite swimmers (4.2 %) than in non-swimmers (20 %) [15]. However, Rodríguez observed no differences in $\dot{V}O_{2peak}$ when comparing postexercise bxb measurements after a 400-m maximal swim and those obtained during maximal, incremental laboratory cycling and running tests and concluded that a maximal 400-m swim is a valid test for $\dot{V}O_{2max}$ determination [32]. Moreover, the same author reported that a group of swimmers who reached their $\dot{V}O_{2max}$ during an incremental 5 × 400-m test attained ~ 95 % of during an all-out 100-m swim [30]. In line with previous results, Chaverri et al. did not find differences in the $\dot{V}O_{2peak}$ reached at 3 swimming distances (50, 100 or 200, and 400 m) swum at maximal speed [4]. This phenomenon is most likely explained by the very fast $\dot{V}O_2$ on-kinetics within the extreme intensity domain exhibited by competitive swimmers, which is exemplified by time constant (τ) mean values of 9 s in 100-m [36], 11 s in 200 m [33, 39, 43], and 17 s (when corrected using the same biexponential model) in 400-m all-out swims [34]. This very high rate of $\dot{V}O_2$ increase, among the fastest reported in the literature, is likely produced by the intense activation of lower limbs and trunk muscles during kicking in the faster swims [36]. Globally, these observations strongly suggest that a 200-m all-out swim yields maximum $\dot{V}O_2$ values, and hence, it can be considered to be a valid and practical test to determine maximal aerobic power during swimming using postexercise measurements in competitive swimmers.

Study limitations

First, the order of the tests could not be randomized because of constraints imposed by the logistics and timing of the study. However, the reliability of $\dot{V}O_{2peak}$ during maximal 200-m tests in elite swimmers is high, as discussed in the "Measured $\dot{V}O_2$ during exercise" section [33]. Second, although we do not anticipate large discrepancies, it would be of interest to investigate swimmers of lower competitive level and younger age to ensure the external validity of the present results, as well as to confirm these findings for the remaining swim strokes.

Practical applications

Using bxb respiratory equipment at the poolside has improved the feasibility and validity of gas exchange assessment in swimming. Specially-designed snorkels, despite the advantage of allowing continuous measurements during exercise and recovery, still have limitations, such as precluding diving starts and flip turns, altering stroke kinematics, modifying the breathing pattern, and causing potentially unbearable discomfort. Using postexercise $\dot{V}O_2$ measurements enables the swimmers to exercise without being hindered by the respiratory equipment and to exploit their maximal potential. However, previous and present results show that BE techniques result in substantial overestimation of $\dot{V}O_{2peak}$ (~ 4–20 %). Considering that elite swimmers have shown to vary their $\dot{V}O_{2peak}$ in ~ 6 % over one competitive season [6], the large measurement error exhibited by the BE techniques (linear and semilogarithmic) largely compromises their ability to monitor progress in elite swimmers. The classical single 20-s measurement technique was also found to underestimate the criterion values by ~3.4–4.5 %. In contrast, the HR/$\dot{V}O_2$ modelling procedure minimizes the error in predicting $\dot{V}O_{2peak}$ (0.1–1.6 % on average), thus providing a valid and accurate method to measure changes in aerobic performance capacity. Moreover, the necessary HR measurements can be taken without any interference in the normal swimming pattern and can provide scientists and coaches with additional information – e. g., training load quantification [13].

Conclusions

All-out, fully unrestricted swimming, in which the swimmer can perform without being hindered by the respiratory equipment, is required to assess cardiorespiratory fitness if the swimming technique has to be maintained and race speed is to be reached. This requires measuring gas exchange during recovery, but accuracy is key for estimating the exercise $\dot{V}O_{2peak}$. From the present study, we may conclude the following: 1) $\dot{V}O_{2peak}$ can be estimated from postexercise measurements with good accuracy after an all-out middle-distance swim (200 m or 400 m), even with a time gap between the cessation of exercise and the first valid $\dot{V}O_2$ measurement; 2) BE methods using linear and semilogarithmic regressions overestimate $\dot{V}O_{2peak}$ by ~4–14 % due to a time-variable delay of the fast component of the $\dot{V}O_2$ off-kinetic response (~10 s on average), which does not affect the HR/$\dot{V}O_2$ modelling technique; 3) the extensively adopted 20-s average method regression of shorter measurement periods (0–20 s) provides more accurate results, but still underestimates $\dot{V}O_{2peak}$ by ~3–5 % due to the rapid decay of $\dot{V}O_2$ during recovery; 4) the HR/$\dot{V}O_2$ modelling technique, based on continuous beat-to-beat HR and postexercise bxb $\dot{V}O_2$ measurements over 20 s, is confirmed as a valid and accurate procedure for estimating $\dot{V}O_{2peak}$ without significant bias (0.1–1.6 %) after a maximal swim in competitive swimmers; and 5) both 200-m and 400-m all-out swims are valid tests for assessing swim-specific $\dot{V}O_{2max}$ in highly trained swimmers. Therefore, the HR/$\dot{V}O_2$ modelling technique appears to be a valid and accurate method for assessing cardiorespiratory and metabolic fitness in competitive swimmers when postexercise measurements are chosen to avoid the burden of respiratory equipment during the swimming exercise.

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Conflict of interest

No conflicts of interest are declared.

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