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… The most beautiful sea
hasn’t been crossed yet.
- *Nazim Hikmet* -

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ABSTRACT

The assessment of oxygen uptake ($\dot{V}o_2$) in swimming is a complex and cumbersome procedure and still faces limitations imposed by the environment and the equipment. There are two different approaches to measure $\dot{V}o_2$ in water: 1) continuous measurement during exercise with a respiratory snorkel, and 2) post-exercise measurement with gas collection via face or mouth masks. However, the use of swimming snorkels modifies swimming technique and hydrodynamics, resulting in lower swimming speeds and impossibility to execute diving starts and turns. To overcome these problems, the backward extrapolation of the oxygen recovery curve is often used for predicting $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ during unimpeded swimming, but error can derive from a delay at the onset of recovery $\dot{V}\mathrm{o}_2$. In this thesis, we first assessed the validity of a mathematical model based on heart rate (HR) and post-exercise $\dot{V}o_2$ kinetics for the estimation of $\dot{V}o_2$ during exercise (**study I**). Then, to assess the validity of this technique in estimating $\dot{V}o_{2\mathrm{peak}}$, we compared $\dot{V}\mathrm{o}_2$ measurements during supramaximal swimming with various commonly adopted estimation methods (**study II**) and distances (200- and 400-m) **study III.** We demonstrate that the new modelling procedure based on postexercise $\dot{V}\mathrm{o}_2$ and HR measurements is a valid and accurate technique for estimating $\dot{V}o_{2\mathrm{peak}}$ in swimmers when used over a maximal 200- or 400-m test, indistinctly, and avoids the estimation bias produced by other commonly used methods. Therefore, this new procedure appears as the method of choice for assessing cardiorespiratory and metabolic fitness in competitive swimmers while swimming fully impeded.

RESUM

L'avaluació del consum d'oxigen ($\dot{V}o_2$) en natació és un procediment complex i farragós degut a les limitacions imposades pel medi aquàtic i l'equipament. Hi ha dos procediments habituals per determinar del $\dot{V}o_2$ en el medi aquàtic: 1) el mesurament continu del $\dot{V}o_2$ mitjançant un sistema de tub respirador, i 2) mesuraments post exercici mitjançant l'ús de màscares facials o bucals. Tanmateix, l'ús de tubs respiratoris modifica la tècnica i la hidrodinàmica, fet que redueix la velocitat i impossibilita les fases subaquàtiques en sortides i viratges. Per superar aquests problemes s'ha utilitzat la retroextrapolació de la corba de recuperació del $\dot{V}o_2$ per predir el $\dot{V}\mathrm{o}_{2\mathrm{pic}}$ durant la natació lliure, però sovint es produeix un error d'estimació derivat d'un retard en l'inici de la recuperació del $\dot{V}o_2$. En aquesta tesi, s'avalua un model matemàtic basat en la cinètica de la freqüència cardíaca (FC) i el $\dot{V}o_2$ post exercici per l'estimació del $\dot{V}o_2$ durant l'esforç (**estudi I**). Posteriorment, per avaluar la validesa del mètode en l'estimació del $\dot{V}\mathrm{o}_{2\mathrm{pic}}$, es van comparar els mesuraments de $\dot{V}o_2$ durant proves de natació supramaximal amb diversos mètodes comunament utilitzats (**estudi II**) i en diferents distàncies (200 i 400 m) (**estudi III**). En aquesta investigació demostrem que el nou procediment de modelatge basat en mesures del $\dot{V}o_2$ post exercici i en la cinètica de la FC és un mètode vàlid i acurat per estimar el $\dot{V}\mathrm{o}_{2\mathrm{max}}$ en nedadors en 200 o 400 m, indistintament, i evita el biaix d'estimació produït per altres mètodes. Per tant, aquest nou procediment es presenta com el mètode a escollir per avaluar, en condicions de natació completament lliure, les capacitats cardiorespiratòria i metabòlica en nedadors de competició.

GLOSSARY

$C(a-\bar{v})\text{o}_2$	Arterious-venous O_2 difference
HR	Heart rate
mean diff. (or Δ)	Mean difference
$p\dot{V}\text{o}_{2\text{peak}}(0-20)$	Predicted $\dot{V}\text{o}_2$ at interval 0-20 s of the recovery period
$p\dot{V}\text{o}_{2\text{peak}}(5-20)$	Predicted $\dot{V}\text{o}_2$ at interval 5-20 s of the recovery period
$p\dot{V}\text{o}_{2\text{peak}}(10-20)$	Predicted $\dot{V}\text{o}_2$ at interval 10-20 s of the recovery period
r^2	Pearson’s coefficient of determination
SD	Standard deviation
SE_E	Standard error of estimate
SV	Cardiac systolic volume
t	A given time during recovery
$\dot{V}\text{o}_2$	Oxygen uptake
$\dot{V}\text{o}_{2\text{max}}$	Maximal oxygen uptake
$\dot{V}\text{o}_{2\text{peak}}$	Peak oxygen uptake
$\dot{V}\text{o}_{2\text{peak}}\text{NLR}$	Peak oxygen uptake estimated by nonlinear regression
BE	Backward extrapolation
BE(20)	BE taken the first 20-s averaged values during recovery
BE(30)	BE taken the first 30-s averaged values during recovery
BE(3x20)	Estimated $\dot{V}\text{o}_2$ using BE (3x20-s averaged values)
BE(4x20)	Estimated $\dot{V}\text{o}_2$ using BE (4x20-s averaged values)
BE(3 ∪4x20)	Estimated $\dot{V}\text{o}_2$ using BE (3- or 4x20-s averaged values)
LOG(20)	BE taken the first 20-s of log values during recovery
LOG(30)	BE taken the first 30-s averaged log values during recovery
LOG(3x20)	Estimated $\dot{V}\text{o}_2$ using BE (3x20-s averaged log values)
LOG(4x20)	Estimated $\dot{V}\text{o}_2$ using BE (4x20-s averaged log values)
LOG(3 ∪4x20	Estimated $\dot{V}\text{o}_2$ using BE (3- or 4x20-s averaged log values)
$\dot{V}\text{o}_{2\text{peak}}(0-20)$	$\dot{V}\text{o}_{2\text{peak}}$ taken as the first 20-s averaged values during recovery
$p\dot{V}\text{o}_{2\text{peak}}(-0-20)$	$\dot{V}\text{o}_{2\text{peak}}$ taken as the last 20-s averaged values during exercise

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LIST OF PUBLICATIONS

This thesis is mainly based on the following publications, herein referred to by their Roman numbers:

I. **Chaverri, D**., Schuller, T., Iglesias, X., Hoffmann, U. and Rodríguez, F. A. (2016). A new model for estimating peak oxygen uptake based on postexercise measurements in swimming. *International Journal of Sports Physiology and Performance*, *11*(4), 419-424.

II. **Chaverri, D.**, Iglesias, X., Schuller, T., Hoffmann, U., and Rodríguez, F. A. (2016). Estimating peak oxygen uptake based on postexercise measurements in swimming. *Applied Physiology, Nutrition, and Metabolism*, *41*, 1-9.

III. Rodríguez, F. A., **Chaverri, D.**, Iglesias, X., Schuller, T., & Hoffmann, U. (2016). Postexercise measurements to estimate maximal oxygen uptake in 200- and 400-m maximal swimming tests. *Scandinavian Journal of Medicine and Science in Sports* (submitted).

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II. **Chaverri D.**, Iglesias X., Schuller T., Barrero A., Štrumbel, B., Hoffmann U., and Rodríguez F.A. (2013) Validity of peak VO2 after a maximal 400-m free swimming test using a new model based on postexercise measurements and heart rate kinetics. In *Proceedings of the 18th Annual Congress of the European College of Sport Science*. Barcelona: Open Print, p. 404. ISBN: 978-84-695-7786-8.

III. **Chaverri, D.**, Iglesias, X., Barrero, A., Schuller, T., Štrumbel, B., Hoffmann, U., and Rodríguez, F.A. VO2 peak measured during 200m is not different from that calculated with a new model after a 200-m maximal swim. In *Proceedings of the 18th Annual Congress of the European College of Sport Science*. Barcelona: Open Print, p. 404. ISBN: 978-84-695-7786-8.

IV. Schuller, T., Hoffmann, U., Iglesias, X., **Chaverri, D**., & Rodríguez, F. A. (2014). Concurrent validity of a new model for estimating peak oxygen uptake based on postexercise measurements and heart rate kinetics in swimming. In Mason B. (editor), *Proceedings of the XIIth International Symposium for Biomechanics and Medicine in Swimming*. Canberra: Australian Institute of Sport, pp. 506-511. ISBN 978-0-646-91868-6.

V. **Chaverri D**., & Rodríguez F. A. (2015). Estimación del consumo de oxígeno pico en natación basado en mediciones post-ejercicio. En Arufe Giráldez V. (ed.), *Actas XI Congreso Internacional de Ciencias del Deporte y Educación Física, Seminario Internacional de Nutrición, Medicina y Rendimiento Deportivo*. Pontevedra: ISBN 978-84-943477-0-2.

VI. **Chaverri D.**, Iglesias X., Rodríguez F.A. (2016). Post-exercise measurements for estimating VO2 peak in 200 and 400-m maximal swims. *III Congreso Internacional de Optimización del Entrenamiento y Readaptación Físico-Deportiva*. Sevilla

VII. **Chaverri D.**, Iglesias X., Rodríguez F.A. Estimación del consumo de oxígeno submáximo basado en mediciones post-ejercicio en natación. *Actas IX Congreso Internacional de la Asociación Española de Ciencias del Deporte*. Toledo

INTRODUCTION

Oxygen uptake during exercise

Since 1799 that Humphrey Davy proved that blood contained both oxygen (O_2) and carbon dioxide (CO_2) the study and analysis of both parameters have experimented a notable progress (Jones et al. 2013). In 1780, Lavoisier and the mathematician La Place were the first to show that a guinea pig consumes O_2 and produces CO_2 and heat; notwithstanding, where this combustion took place remained unclear (Sprigge 2002). A few years later, Heinrich Gustav Magnus constructed the first blood-gas analyser, which would show that arterial blood contained more O_2 and less CO_2 than venous blood and that gas exchange occurs in the muscles (~1837) (Jones and Poole 2013). Davy (~1800), collecting 1 min of his expired air and comparing the measured O_2 and CO_2 with the total air breathed into the bag, was the first person to estimate his own oxygen uptake ($\dot{V}\mathrm{o}_2$) (484 ml·min^{-1}) and CO_2 production ($\dot{V}\mathrm{co}_2$) (447 ml·min^{-1}) (Sprigge 2002).

In 1911 Douglas developed a new instrument to collect expired air, measuring $\dot{V}\mathrm{o}_2$ and $\dot{V}\mathrm{co}_2$ at rest and during exercise. This instrument was a rubber-lined canvas bag, where the expired air was collected through a mouthpiece connected to a valve system. The collection was made following specific time periods (e.g. 20 s) and posteriorly analysing the gas concentration and the total volume considering the factors that could affect the estimations (e.g. barometric pressure, temperature) (DiMenna 2009). In the 1920s, the Nobel Prize in 1922 Hill and his colleagues performed several $\dot{V}o_2$ measurements in humans, and proposed the concept of maximal oxygen uptake

($\dot{V}\mathrm{o}_{2\mathrm{max}}$) (Hale 2008). Posteriorly, in the 1960s, scientists as Karl Wasserman, Brian Whipp, Paolo Cerretelli and Pietro di Prampero achieved significant advances on the field of O_2 uptake assessment (Jones and Poole 2013).

Key to understand the main factors determining $\dot{V}\mathrm{o}_2$ during rest and exercise if the Fick's equation (Fick 1870), which relates cardiac output ($\dot{Q}$), arterious-venous O_2 difference ($C(a-\bar{v})\mathrm{o}_2$) according to the equation:

$$\dot{V}\mathrm{o}_2 = \dot{Q} \cdot C(a-\bar{v})\mathrm{o}_2 \qquad \text{(eq. 1)}$$

On the other hand, $\dot{Q}$ equals the cardiac stroke volume (SV) times the heart rate (HR):

$$\dot{Q} = SV \cdot HR \qquad \text{(eq. 2)}$$

Under the assumption that SV does not significantly change over the first seconds of recovery (Eriksen et al. 1990), changes in HR can be considered as a proxy for changes in $\dot{Q}$, and likewise, the $\dot{V}o_2$/HR ratio can be used a proxy of the arterio-venous O_2 difference:

$$\frac{\dot{V}\mathrm{o}_2}{\mathrm{HR}} \approx C(a-\bar{v})\mathrm{o}_2 \cdot constant \qquad \text{(eq. 3)}$$

Nowadays, $\dot{V}\mathrm{o}_2$ and $\dot{V}\mathrm{o}_{2\mathrm{max}}$ have become key variables in the field of exercise physiology. Both are frequently used to indicate exercise intensity, training effects or cardiorespiratory fitness. There has been great interest in identifying the physiological factors related with these variables and determining the role of these variable in endurance performance in sport sciences. However, until the 1980s, $\dot{V}\mathrm{o}_{2\mathrm{max}}$ assessment were conducted in the laboratory during running and cycling exercise.

Since then, there has been a growing interest in its assessment using a variety of portable and laboratory equipment in other sports (Hale 2008).

Oxygen uptake in swimming

To our knowledge, the first gas collections in swimming were conducted by Liljestrand and Lindhard in 1920, who analysed the respiratory gas volume and other physiological parameters during swimming in a lake (Liljestrand et al. 1920). The evolution of cardiorespiratory measurements in water was largely related to the technological progress and the ability to overcome the limitations imposed by the environment.

We must not forget that performance in swimming consists on the coverage of a distance as fast as possible. The velocity attained during a race is related to the maximal metabolic power (aerobic and anaerobic components) and the energy cost to swim a unit of distance (Zamparo et al. 2011). In this sense, the scientific literature has tried to elucidate the contribution of each energetic system in maximal swimming of different competitive distances. In long distance events the aerobic system plays an important role on the total metabolic power. Rodríguez and Mader, using computer simulation based on experimental data, calculated the relative contribution of the three energy systems (aerobic, glycolytic, and phosphagenic) in freestyle swimming competitive events in top-level swimmers (figure 1).

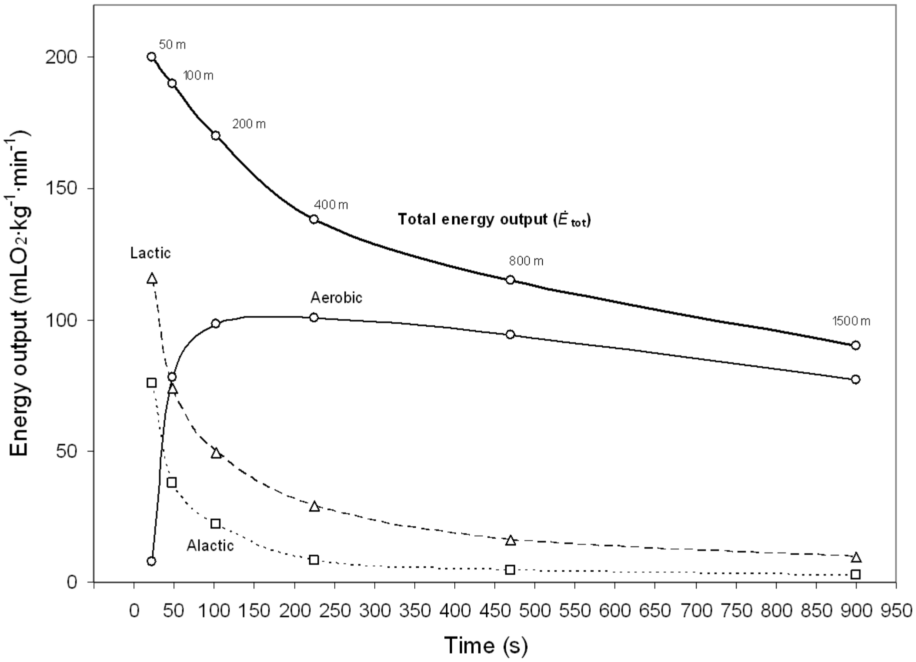


Figure 1. Total energy output ($\dot{E}_{tot}$) and share of the three energy delivery systems during maximal swimming as a function of time at competitive speed in top male swimmers as obtained by computer simulation (Rodríguez et al. 2011).

Thus, the prevalence of anaerobic processes during sprinting events (i.e. ~22-48 s) leads to a progressive predominance of the aerobic processes in middle- (i.e. 200 and 400 m) and long-distance events (i.e. 800 and 1,500 m) (table 1) (Rodríguez and Mader 2011). Other authors have estimated different relative aerobic contributions to maximal metabolic power in middle-distance events like 200-m (~79% (Sousa et al. 2011b), ~72% (Zamparo et al. 2000), and ~87% (Reis et al. 2010b), and 400-m (~86% (Zamparo et al. 2000), ~95% (Reis et al. 2010b), and ~83% in a computer simulation (Rodríguez et al. 2003b) (table 1).

Table 1. Share of energy systems during freestyle swimming competitive events in top-level swimmers obtained by computer simulation. Data are in percentage of total energy output ($\dot{E}_{tot}$) (Rodríguez and Mader 2011).

Distance	Time* (min:s)	Phosphagen (%)	Glycolytic (%)	Aerobic (%)
50 m	0:22.0	38	58	4
100 m	0:48.0	20	39	41
200 m	1:45.0	13	29	58
400 m	3:45.0	6	21	73
800 m	7:50.0	4	14	82
1,500 m	14:50.0	3	11	86

*Reference times for top-level male freestyle swimmers (2008). The relative energy patterns in female swimmers are assumed to be relatively similar for a given distance.

Due to the relevant contribution of the aerobic system to the total metabolic power, already in 100 m sprints, swimmers exhibit high $\dot{V}\mathrm{o}_{2\mathrm{max}}$, in the range of about 55 to 75 ml·kg^{-1}·min^{-1} for males (Holmér 1972; Holmer et al. 1974; Montpetit et al. 1981; Lavoie et al. 1983; Costill et al. 1985a; Rodríguez and Mader 2003b; Raffaelli et al. 2012; Sousa et al. 2014b; de Jesus et al. 2015; Rodríguez et al. 2015; Sousa et al. 2015; Rodríguez et al. 2016) and 50 to 65 ml·min^{-1} for females (Holmér 1972; Costill et al. 1985b; Rodríguez and Mader 2003b; Rodríguez et al. 2015; Rodríguez et al. 2015).

Oxygen uptake assessment in swimming

In 1972, Åstrand and Englesson published an article introducing a swimming flume located in Stockholm, Sweden (Åstrand et al. 1972), and the same year the pioneer article by Holmér, “Oxygen uptake during swimming in man”, was also published (Holmér 1972) (figure 2).

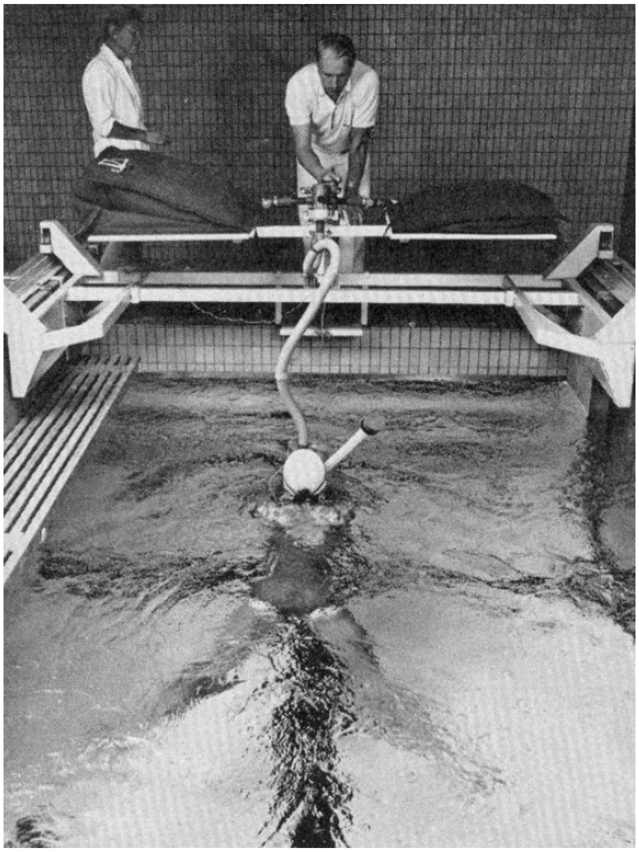


Figure 2. Testing setup for gas exchange measurements using Douglas bags in the Stockholm swimming flume (Holmér 1972).

Thenceforth, the assessment of cardiorespiratory parameters during swimming has been a recurrent topic in scientific literature given the importance that these measurements have on performance analysis. Although the swimming flumes allow the swimmer to express his mechanical and physiological capacities to a great extent, flume swimming does not enable the swimmers to maintain their technique unaltered because of hydrodynamic modifications (i.e. swimmer’s propulsive forces are applied against a water flow instead of on still waters). This is the main reason for the development of other means of collecting respiratory gases while swimming more naturally. Douglas bags, respiratory snorkels, mobile and portable gas analysers have greatly improved our ability to measure $\dot{V}\mathrm{o}_2$ and related cardiorespiratory parameters during free swimming.

To measure in $\dot{V}\mathrm{o}_2$ swimming different adaptations of the respiratory valves previously designed by Hans Rudolph were implemented. However, the use of this equipment often increased the power required to swim at the same speed due to increasing hydrodynamic drag (Sousa et al. 2014a), although recent studies have challenged this view (Barbosa et al. 2010a). However, the fact that swimming speed for a given intensity is lower is undisputed (Montpetit et al. 1981; Keskinen et al. 2001; Barbosa et al. 2010a). Few years later, Toussaint et al. evolved this equipment developing a low-drag respiratory valve system allowing $\dot{V}\mathrm{o}_2$ direct measurements in swimming (Toussaint et al. 1987). We modified the basic design to allow for breath-by-breath (bxb) gas analysis and validated the new snorkel in the laboratory while exercising in the cycle ergometer (Keskinen et al. 2003), using a gas exchange simulator (Rodríguez et al. 2008), and in incremental pool swimming (Keskinen et al. 2001). Figure 3 shows the testing setup for gas exchange bxb measurement during swimming using this specific swimming snorkel as used in the present study.

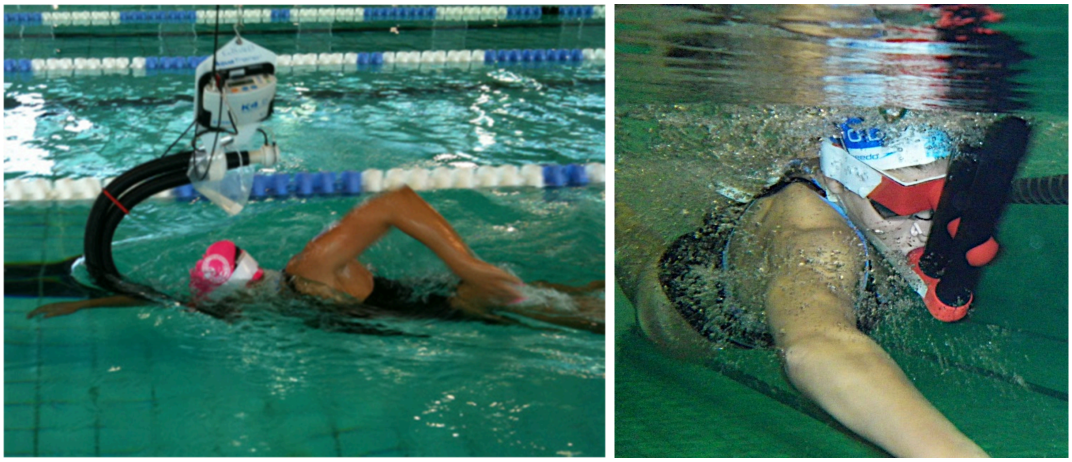


Figure 3. Testing setup for gas exchange breath-by-breath measurement during swimming using a specific swimming snorkel (Keskinen et al. 2003; Rodríguez et al. 2008) connected to a K4 b^2 (Cosmed, Italy) portable gas analyzer. With permission of Ms. Mireia Belmonte, World champion and double Olympic silver medallist.

Postexercise measurements

To overcome the restrictions imposed by the equipment needed to assess $\dot{V}\mathrm{o}_2$ during exercise, Di Prampero et al., were the first to use postexercise measurements to determine $\dot{V}o_2$ at submaximal steady state treadmill walking exercise; the described technique, called backward extrapolation (BE), estimated $\dot{V}\mathrm{o}_2$ by fitting an exponential least squares regression to time zero (t_0); no differences were observed between $\dot{V}\mathrm{o}_2$ measured and estimated using the BE method. Then, this new technique was applied to estimate the oxygen cost of speed skating (Di Prampero et al. 1976). Later, Léger et al., validated this technique during a maximal multistage treadmill running test (Léger et al. 1980); in the first set of experiments, almost identical results were found in $\dot{V}\mathrm{o}_2$ measured during exercise and estimated by BE; in the third set of experiments Léger et al. validated this procedure by comparing $\dot{V}\mathrm{o}_2$ values obtained during the last stage of a multistage running test in the laboratory with $\dot{V}\mathrm{o}_2$ estimated by BE with the same protocol in a field test, obtaining good correlation ($r^2 = 0.96$), low mean difference (1.40 ± 2.84 $ml \cdot kg^{-1} \cdot min^{-1}$), and reduced standard error of the estimate (SE_E) (~5%) between both values. However, when the subject needed to be connected to the respiratory equipment after the cessation of exercise (figure 4), measurement accuracy improved when $\dot{V}o_2$ was corrected for the time needed to connect the subject to the respiratory equipment (~3 s).

Figure 4. Testing setup for postexercise breath-by-breath gas exchange measurement. With permission of Ms. Mireia Belmonte, World champion and double Olympic silver medallist.

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., who found that, although the speed during a maximal multistage test was 10% higher when the BE method was used, measured and estimated $\dot{V}o_{2\mathrm{peak}}$ values were well correlated and the SE_E was low (3.7%). Since then, this technique has often been used for estimating $\dot{V}o_2$ in swimming, e.g. (Lavoie et al. 1983; Jurimae et al.

2007; Zamparo et al. 2008; Zamparo et al. 2012). However, Montpetit et al. suggested that the validity of the BE technique in swimming was 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 (Montpetit et al. 1981). In this sense, previous studies conducted with the Douglas bag technique reported a time delay of 12 to 35 s at the onset of the $\dot{V}o_2$ recovery curve after supramaximal exercise (Di Prampero et al. 1973; Katch 1973; Roberts et al. 1978). Recent studies using bxb measurements confirmed the existence of a delay of ~3-14 s (Rodríguez 1999; Rodríguez et al. 2016; Sousa et al. 2015; Chaverri et al. 2016a). This delay at the onset of the $\dot{V}o_2$ recovery curve was likely to be the cause of the overestimation (20%) described by Lavoie et al. after a supramaximal 400-m swim when $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was estimated by BE using postexercise Douglas bags measurements (Lavoie et al. 1983).

To circumvent this problem, Lavoie et al. proposed a simplified procedure based on a single 20-s postexercise Douglas bag gas collection upon recovery as a good and practical indicator of $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in swimming (Lavoie et al. 1983). Two years later, the simplified procedure was validated by Costill et al. showing a high correlation with the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ measured during a 7 min of tethered breaststroke swimming, although observing a small decline in $\dot{V}o_2$ during the first 20 s yielding a ~6% underestimation of measured values. However, the question persists whether the time-variant delay in getting the first breaths upon recovery after the free swimming exercise could affect the validity and precision of the estimations.

Peak and maximal oxygen uptake

It is well known that competitive performance depends on the swimmer's maximal metabolic power (aerobic and anaerobic energy sources) and the energy cost to swim a unit distance (Di Prampero et al. 1974; Toussaint et al. 1990; Barbosa et al. 2010b; Zamparo et al. 2011). Therefore, $\dot{V}\mathrm{o}_{2\mathrm{max}}$, indicator of maximal aerobic power, is considered an important performance factor. In fact, several authors reported that $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ or $\dot{V}\mathrm{o}_{2\mathrm{max}}$ were good, though —but not excellent— performance predictors (Costill et al. 1985b; Rodríguez et al. 2003a; Reis et al. 2010a; Rodríguez et al. 2016), even in shorter distances such as 100 m (Rodríguez et al. 2003a; Latt et al. 2009; Rodríguez et al. 2016). For instance, $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was shown to be largely related to performance in free 100-m ($r^2 = 0.62$) (Rodríguez et al. 2003a), 365.8 m ($r^2 = 0.64$) (Costill et al. 1985b), 400 m ($r^2 = 0.56$) (Rodríguez et al. 2003a), and 800 m ($r^2 = 0.32$) (Santeusanio) in competitive swimmers.

Incremental tests have been mostly used to measure $\dot{V}\mathrm{o}_{2\mathrm{max}}$ in swimmers (see (Sousa et al. 2014a) for a review). Instead, few studies have assessed directly measured $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in elite swimmers in pool conditions (and not in treadmill running, ergometer cycling or arm cranking, or swimming flume) within the range of race speed and time. Concerning the aerobic (oxidative) energy rate contributions to maximal metabolic power, high mean relative values have been reported for maximal swims over 200 m: 79% (Sousa et al. 2011b), 72% (Zamparo et al. 2000), 87% (Reis et al. 2010b), and 58% (Rodríguez and Mader 2011) using computer simulation based on experimental data; for 400 m maximal swims mean values were: 86% (Zamparo et al.

2000), 95% (Reis et al. 2010b), and 83% and 73% using computer simulation (Rodríguez and Mader 2003b; 2011).

The question of whether $\dot{V}\mathrm{o}_{2\mathrm{max}}$ can be attained during maximal incremental and/or all-out swimming is controversial but key to the physiological evaluation of swimmers. In his pioneer work, Holmér compared $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ measured using the Douglas bag method in the swimming flume, treadmill running and cycling, and found higher $\dot{V}o_{2\mathrm{peak}}$ in running than in swimming (Holmér 1972). Some years later, bxb technology during recovery, Rodríguez did not found differences in $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ between a 400-m maximal swim and incremental laboratory cycling and running tests (Rodríguez 2000). The later results were attributed to very fast $\dot{V}\mathrm{o}_2$ on-kinetics of competitive swimmers (Rodríguez et al. 2003a; Sousa et al. 2011a; Sousa et al. 2011b; Rodríguez et al. 2016). This issue needs to be clarified at least within the limits of what can be called “swim-specific” $\dot{V}\mathrm{o}_{2\mathrm{max}}$ determination, i.e. the maximal $\dot{V}\mathrm{o}_2$ attainable during supramaximal swimming.

Oxygen kinetics in swimming

$\dot{V}\mathrm{o}_2$ kinetics has been analyzed through mathematical modeling of the constant work rate exercise, both in on- and off-transient responses (Whipp et al. 2005). The exponential nature of the response could indicate first or second order kinetics profiles (DiMenna et al. 2009), but first-order kinetics (figure 5) mandates on-off symmetry, which means that the change in $\dot{V}\mathrm{o}_2$ that occurs when the contractile activity is ceased must be a mirror image of that which occurred when it was commenced (Rossiter et al. 2005). In fact, this analysis has shown symmetry during moderate intensity exercise (under the lactate threshold, LT) since $\dot{V}\mathrm{o}_2$ exponentially increases at the onset of exercise (on-fast component) towards a steady state, decreasing rapidly at the offset of exercise (off-fast component) (Paterson et al. 1991; Özyener et al. 2001; Scheuermann et al. 2001; Kilding et al. 2005).

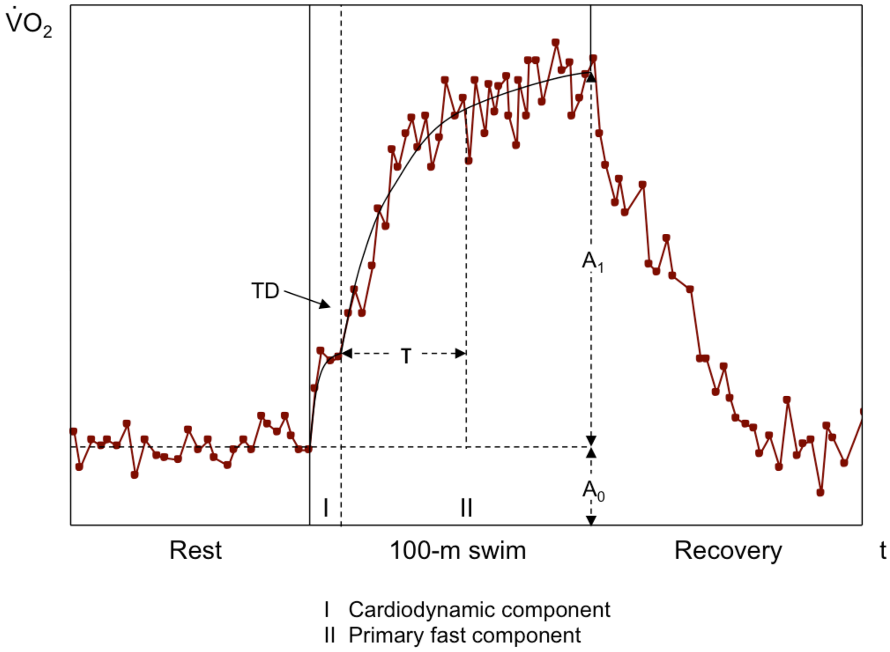


Figure 5. Monoexponential function modelling of the on-transient $\dot{V}\mathrm{o}_2$ kinetics during 100-m swimming exercise. The model includes the amplitude during rest (A_0) and the exercise asymptotic amplitude (A_1) during exercise (i.e. 100-m swim). The physiologically relevant amplitude for the primary exponential component during Phase II (primary or fast component) is defined as the total amplitude at the end of the exercise ($A_p=A_0+A_1$). The time constant (τ) defines the rate of increase of VO_2 during the exercise (Rodríguez et al. 2016)

For heavy exercise (above the LT), the $\dot{V}\mathrm{o}_2$ on-dynamics is more complex and requires a second-order model, since $\dot{V}\mathrm{o}_2$ is additionally increased (on-slow component) after the on-fast component (Burnley et al. 2007; Jones et al. 2009). The equation characterizing the on-transient $\dot{V}\mathrm{o}_2$ kinetics using a double-exponential model is (Özyener et al. 2001):

$$\dot{V}\mathrm{o}_2(t) = \mathrm{A}_0 + A_\mathrm{p} \cdot \left(1 - \mathrm{e}^{-(t-\mathrm{TD}_1)/\tau_1}\right) + \left(1 - \mathrm{e}^{-(t-\mathrm{TD}_\mathrm{p})/\tau_2}\right) \qquad \text{(eq. 4)}$$

where $\dot{V}\mathrm{o}_2$ (t) is the weight-related $\dot{V}\mathrm{o}_2$ at time t, A_0 is the $\dot{V}\mathrm{o}_2$ at rest (ml·kg^{-1}·min^{-1}), and A_1 and A_2 (ml·kg^{-1}·min^{-1}), TD_1 and TD_2 (s), and τ_1 and τ_2 (s) are the corresponding amplitudes, time delays and time constants of the fast ($_1$) and slow ($_2$) components, respectively.

The off-transient $\dot{V}\mathrm{o}_2$ kinetics using different double-exponential models with independent time delay for the fast and slow components is (Özyener et al. 2001):

$$\dot{V}\mathrm{o}_2(t) = \mathrm{A}_0 + A_1 \cdot \left(\mathrm{e}^{-(t-\mathrm{TD}_1)/\tau_1}\right) + A_2 \cdot \left(\mathrm{e}^{-(t-\mathrm{TD}_2)/\tau_2}\right) \qquad \text{(eq. 5)}$$

where parameters are as in equation 4, applied now to $\dot{V}\mathrm{o}_2$ during the recovery period after exercise.

In swimming, Rodríguez et al. were the first to measure bxb gas exchange, making it possible to characterize $\dot{V}\mathrm{o}_2$ on-kinetics during 100- and 400-m all-out swims (Rodríguez et al. 2003a) (figure 6). Since then, this topic has attracted a lot of attention among swimming scientists (see (Sousa et al. 2014a) for a review). $\dot{V}\mathrm{o}_2$ on-kinetics parameters, such as the time constant τ_p or the time delay (TD_p) of the $\dot{V}\mathrm{o}_2$ on-kinetics fast or principal component, have been shown also to be related with swimming performance, and $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ amplitude and principal component time delay combined was found to explain 46% of the variance in 100-m performance (Rodríguez et al. 2016), although other studies failed to show this relationship (Rodríguez et al. 2003a). Globally, previous results supports the notion that $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ attainable during a specific distance, which depends on the rate of increase of $\dot{V}\mathrm{o}_2$, the duration of exercise, and, when the limits are reached, on $\dot{V}\mathrm{o}_{2\mathrm{max}}$. This issue needs to be clarified, at least within the limits of what can be called “swim-specific” $\dot{V}\mathrm{o}_{2\mathrm{max}}$ determination, i.e. the maximal $\dot{V}\mathrm{o}_2$ attainable during supramaximal swimming.

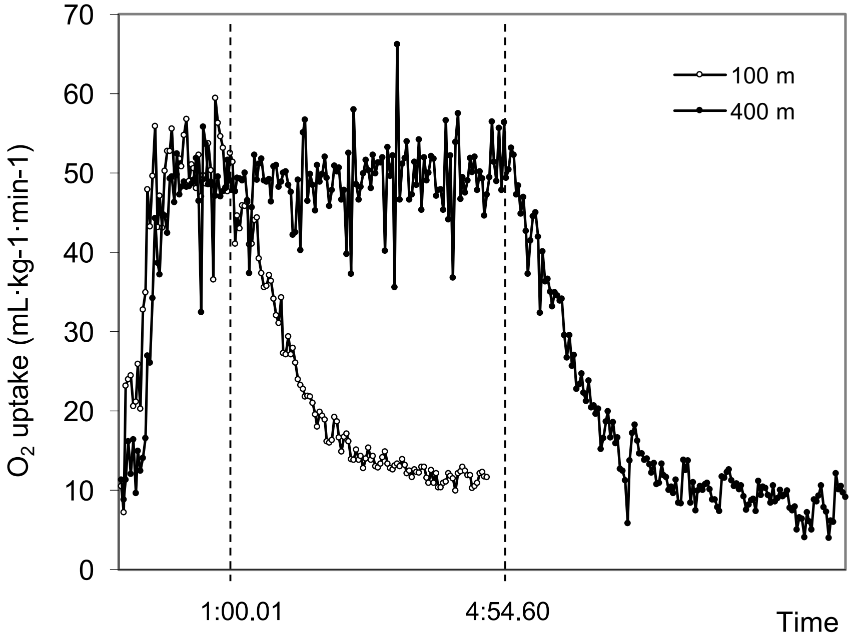


Figure 6. Oxygen uptake measured breath-by-breath (raw data) in one swimmers during exercise and recovery after 100-m and 400-m maximal swims (Rodríguez et al. 2003a).

Contrary to exercise, the kinetics of $\dot{V}\mathrm{o}_2$ during recovery (i.e. off-transient kinetics) is largely unexplored. Contrary to exercise, the kinetics of $\dot{V}\mathrm{o}_2$ during recovery (i.e. off-transient kinetics) is largely unexplored. One study shows, though, that the on- and off-transient $\dot{V}\mathrm{o}_2$ kinetics responses from rest to a square-wave transition exercise at the severe-intensity exercise domain (i.e. 100% of $\dot{V}\mathrm{o}_{2\mathrm{max}}$) in four groups of athletes (swimmers, runners, rowers and cyclists) of comparable level are well described by a double exponential model and are symmetrical in shape (mirror image) and suggests that sport discipline- or exercise-related differences would contribute to distinct off-transient $\dot{V}\mathrm{o}_2$ kinetics pattern at this particular exercise domain (Sousa et al. 2015).

AIMS

The most general objective of this investigation was to develop and assess the validity and accuracy of a new model for estimating peak oxygen uptake ($\dot{V}\mathrm{o}_{2\mathrm{peak}}$) based on postexercise measurements in swimming, overcoming the restrictions imposed by the cardiorespiratory equipment and the problems observed in the current methods of estimation. This general objective can be divided into the following aims, which are addressed in specific papers (in Roman numbers):

(I) A new model for estimating peak oxygen uptake based on postexercise measurements in swimming:

1. To assess the validity of a new model based on heart rate and $\dot{V}\mathrm{o}_2$ off-kinetics for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in swimming by comparing directly measured values with those predicted by the model and estimated from a single 20-s recovery measurement.
2. To investigate different recovery intervals in an attempt to enhance the accuracy of $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ estimation using the model.

(II) Estimating peak oxygen uptake based on postexercise measurements in swimming:

1. To elucidate the validity of commonly used techniques based on postexercise $\dot{V}\mathrm{o}_2$ measurements in estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in supramaximal swimming, including the recently developed HR-$\dot{V}\mathrm{o}_2$ modelling procedure based on the Fick's principle.

2. To determine which is the most valid and accurate procedure for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ after a supramaximal swim.

(III) Postexercise measurements to estimate maximal oxygen uptake in 200- and 400-m maximal swimming tests:

1. To assess the validity of postexercise $\dot{V}\mathrm{o}_2$ measurements in estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ following an unimpeded maximal swim when a time-variant delay occurs between the cessation of exercise and the start of gas collection for analysis.
2. To test the hypothesis that 200- and 400-m supramaximal swimming tests are equally valid for swim-specific $\dot{V}\mathrm{o}_{2\mathrm{max}}$ assessment in competitive swimmers.

METHODS

Participants

Forty-one swimmers, 23 female and 18 male, were recruited for the different studies in this investigation. Subjects were swimmers from eight countries (Australia, Brazil, China, Great Britain, Netherlands, Slovenia, Spain, and Tunis). Selection criteria were to have competed internationally during the previous season and/or being preselected as a member of their national and/or Olympic teams. Their physical characteristics and performance level are presented in table 2.

Table 2. Physical characteristics and performance level of the participants.

	Females (n=18)	Males (n=18)	All (n=41)
Age (years)	20.3 ± 3.7	22.4 ± 3.5	21.2 ± 3.7
Height (cm)	173.3 ± 5.8	186.3 ± 5.9	179.0 ± 8.7
Body mass (kg)	64.3 ± 5.8	80.4 ± 7.3	71.4 ± 10.3
FPS*	850 ± 71	830 ± 47	841 ± 62

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

The sample of Study I was composed by 34 swimmers, including 18 women (mean ± SD FINA Points Score 856±75; age 20.8 ± 3.5 years, height 173.2 ± 5.8 cm, body mass 64.5 ± 5.6 kg) and 16 men (age 22.7 ± 3.6 years, height 186.8 ± 6.0 cm, body mass 80.8 ± 7.7 kg).

For Study II the sample was composed by 31 swimmers, 18 women (FINA Points Score 856 ± 75; age 20.3 ± 3.8 years, height 172.9 ± 5.4 cm, body mass 63.3 ± 5.4 kg) and 13 men (FINA Points Score 840 ± 44; age 22.2 ± 2.9 years, height 187.9 ± 6.0 cm, body mass 82.1 ± 7.2 kg).

In study III two series were conducted. In series A, 8 female swimmers participated (FINA Points Score 806 ± 64; age 19.3 ± 2.3 years, height 175.4 ± 6.1 cm, body mass 65.8 ± 5.4 kg). In series B, 17 swimmers were recruited, 12 women (FINA Points Score 840 ± 63; age 19.7 ± 4.2 years, height 171.6 ± 5.2 cm, body mass 62.3 ± 6.2 kg) and 5 men (FINA Points Score 810 ± 43; age 22.1 ± 2.6 years, height 182.6 ± 3.3 cm, body mass 76.0 ± 5.7 kg).

Procedures

All tests in the three studies were conducted at a 50-m indoor pool (water temperature 26-27ºC, air temperature 27-28ºC). Figure 7 schematizes data collection procedures and derived variables for the three studies. In **studies I and II**, the participants carried out a ~30 min standard warm-up followed by 10 min of passive recovery on the pool side while the respiratory equipment was set up and calibrated for the measurements. Then, the swimmers completed an all-out 200-m front crawl swim using the swimming snorkel to determine exercise $\dot{V}\mathrm{o}_{2\mathrm{peak}}$. After exercise the swimmers remained for 3 minutes in an upright position and immersed into the water to the mid-sternum. In-water starts and touched open turns with no underwater gliding were performed.

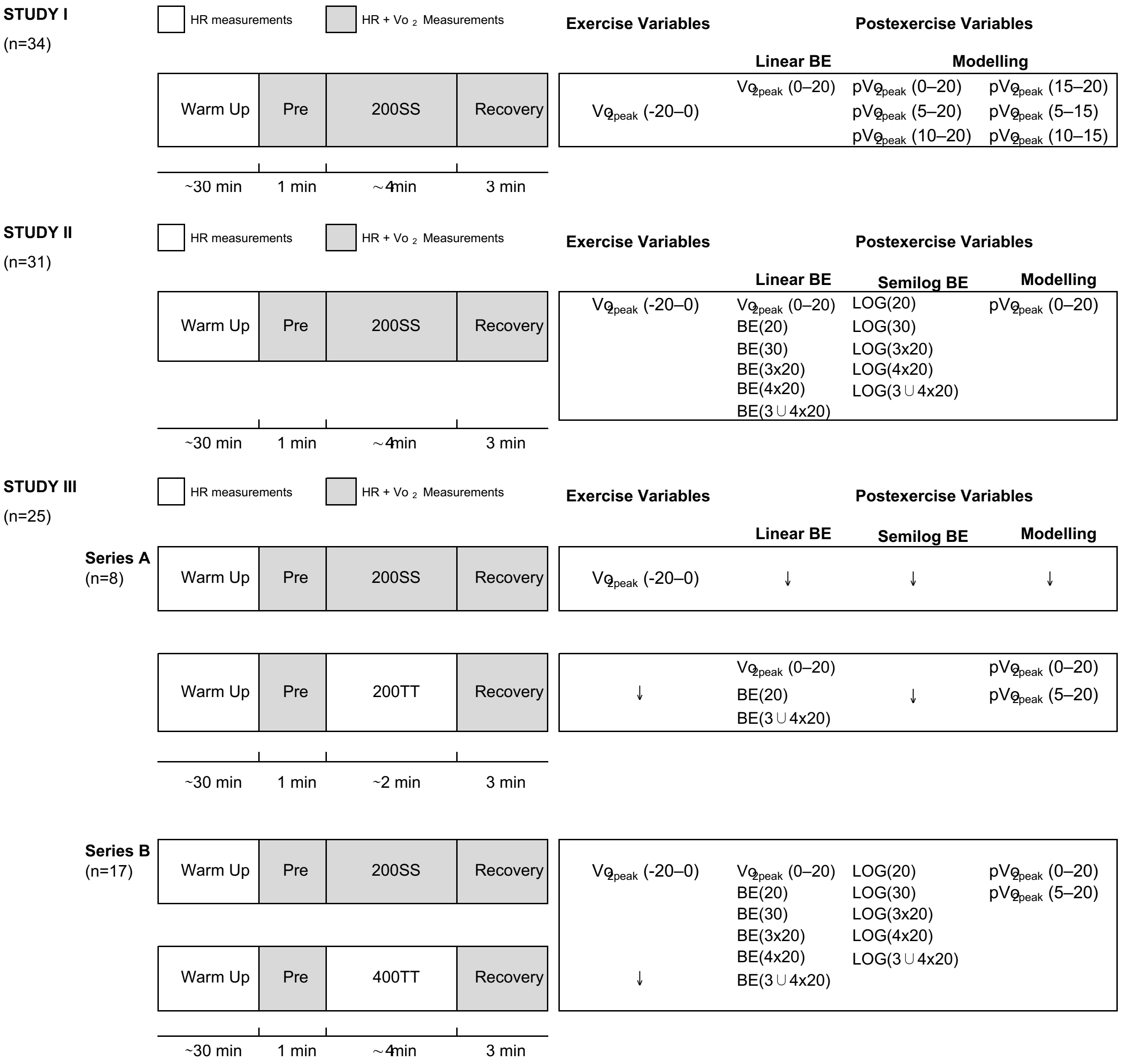


Figure 7. Schematic representation of the experimental procedures for the three studies. In the timeline blocks, grey shadowed areas denote continuous $\dot{V}o_2$ and heart rate measurements, whereas white areas denote heart rate measurements only.

In **study III**, a separate session with at least 24 h between tests was carried out. In series A, the subjects performed a 200-m all-out time trial test in front crawl stroke (200TT). Start was given as in competition and the swimmers, who swam alone, were instructed to achieve the best time possible. In series B, following the same general procedure as in series A, the swimmers performed a 400-m all-out test in front crawl stroke (400TT).

Parameters and equipment

For the assessment of the cardiac and cardiopulmonary gas exchange responses to exercise and recovery, non-invasive methods were used and HR, $\dot{V}\mathrm{o}_2$, and performance recorded.

Heart rate

HR was measured continuously using waterproof monitors (CardioSwim, Freelap, Fleurier, Switzerland) which record beat-by-beat R-R intervals with a belt who contains two chest electrodes wired to a monitoring device that can be unloaded on a computer after the recording.

Figure 8. Waterproof heart rate Freelap monitors and bacons for the recording of heart rate and swimming time laps, time, and speed.

The monitors also recorded the lap times using signalling transmitters. Portable beacon transmitters (TX H2O, Freelap, Fleurier, Switzerland) were placed at both ends of the pool to ensure the recording of each lap (figure 8).

Oxygen uptake

In all tests, $\dot{V}\mathrm{o}_2$ was measured bxb using a telemetric portable gas analyser (K4 b^2, Cosmed, Italy). For direct measurements in the pool, the swimmer was connected to the gas analyser through a validated, low hydrodynamic resistance, respiratory snorkel and valve system (Keskinen et al. 2003; Rodríguez et al. 2008) (figures 3, 9).

When $\dot{V}\mathrm{o}_2$ was measured during recovery, after the swimmer had swum completely unimpeded, expiratory gases were collected using a Hans-Rudolph 7400 silicone oro-nasal mask (Hans Rudolph Inc., Shawnee, Kansas, USA), which was firmly applied immediately after the swim with care to avoid leakage and to minimise the time before the first respiratory data was obtained (figure 4). The swimmers had been instructed about the proper technique before the swims.

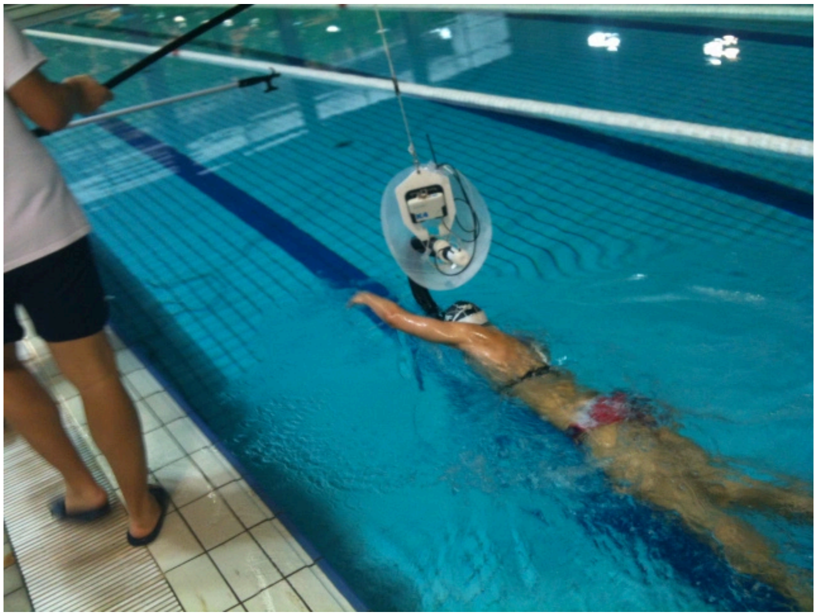


Figure 9. Testing setup for the direct measurement of gas exchange during swimming using a swimming snorkel and a telemetric gas analyser.

Performance

For the swimming time trials, performance was evaluated by manually recording time to the nearest 0.01 s by three experimented timers, one of them the swimmer's personal coach. The median values were used for analysis.

Data processing

In the three studies measured bxb $\dot{V}o_2$ and beat-by-beat HR data were time-aligned to the start of the measurements, 1-s interpolated, and plotted against time using spread sheets (Excel^{TM}, Microsoft, USA).

Measured $\dot{V}o_{2\text{peak}}$ during exercise

To determine a $\dot{V}o_{2\text{peak}}$ value used as a criterion for comparisons, in each one of the three studies $\dot{V}o_{2\text{peak}}(-20-0)$ was computed by averaging the values directly measured over the last 20 s of exercise (t_{-20}–t_0). The 20-s duration during the end of the exercise period was chosen, (1) to ensure that only last swimming-lap data were used, as $\dot{V}\mathrm{o}_2$ usually decreases during the turns; (2) to minimize the influence of inter-breath fluctuations (i.e. improvement of signal-to-noise ratio); (3) to prevent too high $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ values frequently obtained when using shorter time intervals (de Jesus et al. 2014); and (4) as previous work showed that 20-s average values produced the same $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ than the total amplitude of the mono-exponential equation fitting the $\dot{V}\mathrm{o}_2$ on-kinetics during 200-m maximal swims (Rodríguez et al. 2015).

In **study II**, an additional $\dot{V}\mathrm{o}_{2\mathrm{peak}}(\mathrm{NLR})$ value was calculated by fitting $\dot{V}\mathrm{o}_2$ data to a nonlinear least-square regression technique (Matlab R2010b, Mathworks, USA). For the analysis of $\dot{V}\mathrm{o}_2$ kinetics, the first two phases of the generally adopted 3-phase model were identified, since the exercise duration and intensity constrained the appearance of the slow component (Scheuermann et al. 2003). Phase I (cardio-dynamic component) was determined as the time from the onset of exercise to a point of sharper increase in $\dot{V}\mathrm{o}_2$, and its duration was computed as a time delay for the primary component (TD_p). Phase II (principal component) parameters were estimated using a mono-exponential model according to the following equation:

$$\dot{V}\mathrm{o}_2(t) = A_0 + A_\mathrm{p} \cdot \left(1 - \mathrm{e}^{-(t-\mathrm{TD_p})/\tau_\mathrm{p}}\right) \qquad \text{(eq. 6)}$$

where t (s) is the time from the onset of exercise; A_0 is the baseline amplitude; A_p is the amplitude of the principal component; TD_p (s) is the time delay of the first exponential term and equals the duration of phase I (cardio-dynamic component); and τ_p is the time constant of the principal component. The total amplitude (A_tot) was calculated as

$A_{tot} = A_0 + A_p$. The reliability of $\dot{V}o_{2peak}$ measurements was characterized by a typical error (TE) of 3.1% (95% confidence interval, 95% CI: 1.1–5.1%; $n = 9$) (Rodríguez et al. 2015).

Estimated $\dot{V}o_{2peak}$ using modelling procedures

The proposed new model relies on the Fick's principle relating cardiac output ($\dot{Q}$) with $\dot{V}o_2$ and arterious-venous O_2 difference ($C(a - \bar{v})o_2$) according to the equation:

$$\dot{V}o_2 = \dot{Q} \cdot C(a - \bar{v})o_2 \qquad \text{(eq. 7)}$$

On the other hand, $\dot{Q}$ equals the cardiac stroke volume (*SV*) times the HR:

$$\dot{Q} = SV \cdot HR \qquad \text{(eq. 8)}$$

Under the assumption that SV does not significantly change over the first seconds of recovery (Eriksen et al. 1990), changes in HR can be considered as a proxy for changes in $\dot{Q}$, and likewise, the $\dot{V}o_2$/HR ratio can be used a proxy of the arterio-venous O_2 difference:

$$\frac{\dot{V}o_2}{\mathrm{HR}} \approx C(a - \bar{v})o_2 \cdot constant \qquad \text{(eq. 9)}$$

Based on these two assumptions, the mathematical model computes "predicted" $\dot{V}o_2$values ($p\dot{V}o_2$) based on synchronized postexercise $\dot{V}o_2$ and HR measurements (equation 4), and HR at the end of exercise. Thus, at a given time *t* during the recovery period, $p\dot{V}o_2$ can be calculated according to the equation:

$$p\dot{V}o_2(t) = \frac{\dot{V}o_2(t)}{\mathrm{HR(t)}}\mathrm{HR}_{\mathrm{end-exercise}} \qquad \text{(eq. 10)}$$

where, $p\dot{V}o_2(t)$ is the predicted (modelled) postexercise $\dot{V}o_2$ 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 $HR_{\text{end-exercise}}$ is the highest value of the last 10-s average HR at the end of exercise (excluding single peaks higher than 5 bpm than the rest, corresponding to ~1 *SD* from mean HR during the last 10 s of exercise).

In the **study I**, $\dot{V}o_{2\text{peak}}(-20-20)$, i.e. last 20-s average during exercise, which was taken as criterion variable, was compared with $p\dot{V}o_2$ at different time intervals (*t* = 0–20, 5–20, 10–20, 15–20, 5–15, and 10–15 s), which were expressed as $p\dot{V}o_2(0-20)$, $p\dot{V}o_2(5-20)$, $p\dot{V}o_2(10-20)$, $p\dot{V}o_2(15-20)$, $p\dot{V}o_2(5-15)$, and $p\dot{V}o_2(10-15)$ (see figure 10). In **study II**, based in previous findings that determined that $p\dot{V}o_2$ at time interval *t* = 0–20 was the most accurate procedure to estimate $\dot{V}o_{2\text{peak}}$, only $p\dot{V}o_2(0-20)$ was calculated.

In the **study III**, modelling procedures were used to estimate $\dot{V}o_{2\text{peak}}$ after a 200- and 400-m maximal swims, and $p\dot{V}o_2(0-20)$ and $p\dot{V}o_2(5-20)$ were computed for comparison in an attempt to leave out the time needed to start the measurements when the swimmer performed unimpeded (~ 3–5 s).

Estimated $\dot{V}o_{2peak}$ by backward extrapolation

Two different approaches were taken to estimate $\dot{V}o_{2\text{peak}}$ from $\dot{V}o_2$ kinetics during the recovery period using the BE technique, linear and semilogarithmic. First, six different procedures were used to estimate $\dot{V}o_{2\text{peak}}$ by BE: 1) $\dot{V}o_{2\text{peak}}(20-0)$: average values measured within the first 20 s of recovery ($t_0 - t_{20}$); 2) BE(20): estimated value calculated by BE to time zero (t_0) of the first 20-s values of the $\dot{V}o_2$ recovery curve; 3) BE(30): estimated $\dot{V}o_{2\text{peak}}$ by BE to t_0 of the first 30-s values of the $\dot{V}o_2$ recovery curve; 4)

BE(3x20): BE value calculated from the first three 20-s average values of the $\dot{V}\mathrm{o}_2$ recovery curve; 5) BE(4x20): BE value calculated from the first four 20-s average values of the $\dot{V}\mathrm{o}_2$ recovery curve; and 6) BE(3∪4x20): estimated value calculated by BE to t_0 of the best linear regression fit (3x20-s or 4x20-s) of the $\dot{V}\mathrm{o}_2$ recovery curve.

Second, the same estimations were performed using the semilogarithmic procedure (LOG), i.e. plotting the logarithms of the $\dot{V}\mathrm{o}_2$ measured values as a function of recovery time and backward extrapolating to t_0 as in the original paper of Léger et al. (Léger et al. 1980). Using analogous notation, five different calculations were computed to estimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$: 1) LOG(20); 2) LOG(30); 3) LOG(3x20); 4)LOG(4x20); and 5) LOG(3∪4x20). Figure 7 summarizes which BE procedures were implemented to estimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in each study.

Statistical analysis

For the three studies the descriptive data are expressed as means and standard deviations (± *SD*), and mean differences (mean Δ). The normality of the distributions and homogeneity of variance were checked by the Shapiro–Wilks and Levene tests, respectively. In **study II**, one-way analysis of variance (ANOVA) with repeated measures (RM-ANOVA) and post hoc Tukey test, when appropriate, were used for multiple comparisons between the criterion variable and each of the postexercise measured and predicted values. The same statistical procedure (RM-ANOVA) was applied in **studies II** and **III** (series A), though in this case, the post hoc Bonferroni test was chosen. In both studies, sphericity was checked by Mauchly test. In series B, a two-way RM-ANOVA and post-hoc Bonferroni test, when appropriate, were used for multiple comparisons between exercise (criterion) and postexercise estimates, comparisons between the two tests (TT200, TT400 m), and the interaction test/procedure.

In the three studies, the Pearson's coefficient of determination (r^2) was used to assess correlation between variables and the goodness-of-fit of regression models. However, in **study II**, Pearson's coefficient of determination (r^2) was further assessed by using a cross-validation (CV) procedure. Data were split into 2 half subsamples (CV_1, CV_2) and their regression parameters were calculated and then used to estimate a set of predicted values for the other subsample. r^2 for the observed and predicted data for each subsample (r^2_{CV1}, r^2_{CV2}) were then computed.

For the three studies, the SE_E, expressed as absolute values and percentage of the mean, and the limits of the 95% CI were calculated. Differences between measured and estimated $\dot{V}o_{2peak}$ and the level of agreement (mean ± 1.96 *SD*) were analysed graphically using Bland–Altman difference plots (Bland et al. 1986). Under- and overestimation are defined as the difference between estimated and criterion mean values expressed in percentage of the criterion's mean. The level of significance was set at $p < 0.05$. Statistical analyses were conducted using SPSS for Windows (version 15 for the **study I** and 18 for **studies II and II** (SPSS Inc., PASW Statistics for Windows, Chicago, USA).

Ethical considerations

The experimental protocols had received the approval from the Ethics Committee for Clinical Sport Research of Catalonia and follow the legal requirements and the 2004 Declaration of Helsinki. All participants volunteered and did not receive economic compensation. They were fully informed of the procedures, measurements and potential risk, after which they gave their written informed consent to participate in the study.

SUMMARY OF RESULTS

The results from this investigation demonstrate that the proposed model based on HR kinetics and postexercise $\dot{V}\mathrm{o}_2$ measurements is a valid procedure for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ after a maximal 200- and 400-m swim in competitive swimmers.

The new procedure shows an optimal predictive capacity within the first 20 s after the cessation of exercise cessation, overcoming the problem of under- and overestimation reported by BE procedures, and allows the subject to swim completely unimpeded and, hence, to achieve the full use of high-speed swimming technique and the specifically trained muscle mass in pool conditions. A summary of the individual study-specific results is detailed below.

A new model for estimating peak VO2 based on postexercise measurements in swimming (study I)

Figure 10 shows an example of HR and $\dot{V}\mathrm{o}_2$ over the last 30 s of the exercise and the immediate recovery, as well as the predicted $p\dot{V}\mathrm{o}_2$ values for different postexercise intervals in one participant. As can be seen in the figure, $p\dot{V}\mathrm{o}_2$ values do not decline over the first 20 seconds after the cessation of exercise, which is likely the time for the onset of changes in $C(a-\bar{v})\mathrm{o}_2$ perceivable in the exhaled air.

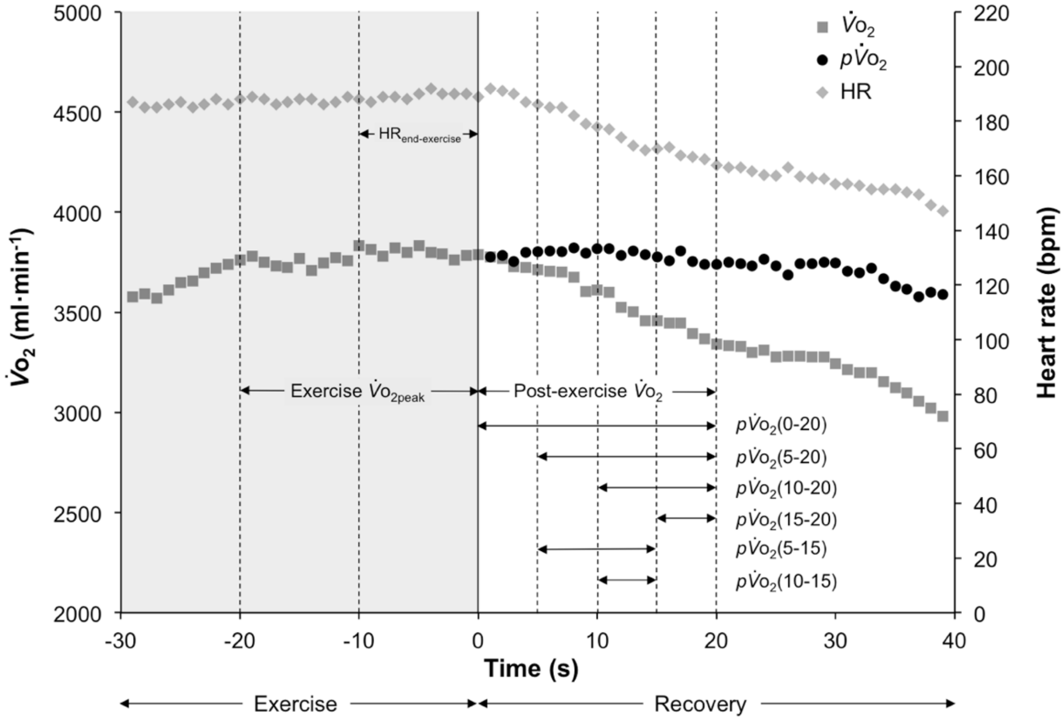


Figure 10. Heart rate (light grey diamonds) and $p\dot{V}\mathrm{o}_2$ (dark grey squares) kinetics over the last 30 s of exercise and immediate recovery during a 200-m maximal swim in one swimmer. Vertical lines indicate time intervals during exercise ($t < 0$) and recovery ($t > 0$). In black circles, modelled (predicted) values ($p\dot{V}\mathrm{o}_2$) during recovery. Short dashed lines indicate different time intervals used for comparisons.

Postexercise $\dot{V}\mathrm{o}_2(0-20)$ underestimated exercise values by 3.3% (116 ml·min^{-1}). All predicted $p\dot{V}\mathrm{o}_2$ were highly correlated (r^2 = 0.856-0.963) and were not different from the criterion value (p > 0.76-1.0). The best $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ estimates was provided by $p\dot{V}\mathrm{o}_2(0-20)$ (r^2 = .963; mean diff. = 17 ml·min^{-1}, SE_E = 3.8%) followed by $p\dot{V}\mathrm{o}_2(5-20)$ (r^2 = 0.943; mean diff. = 13 ml·min^{-1}, SE_E = 4.7%). However, the best agreement between exercise $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ and $p\dot{V}\mathrm{o}_2$ was observed in $p\dot{V}\mathrm{o}_2(0-20)$.

Estimating peak oxygen uptake based on postexercise measurements in swimming (study II)

As shown in figure 11 and table 3, irrespectively of the calculation procedure, all BE techniques overestimated exercise $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ as a consequence of the time-variable delay at the immediate recovery (9.1 ± 4.8 s; range = 2-22 s; 95% IC = 7.3-10.9 s).

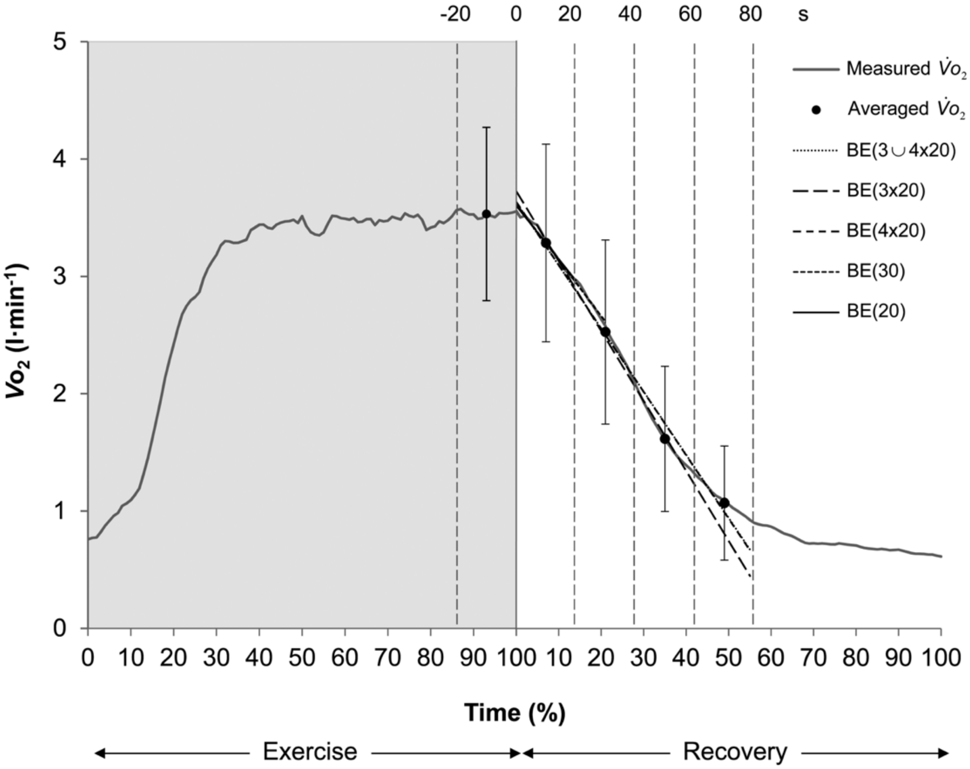
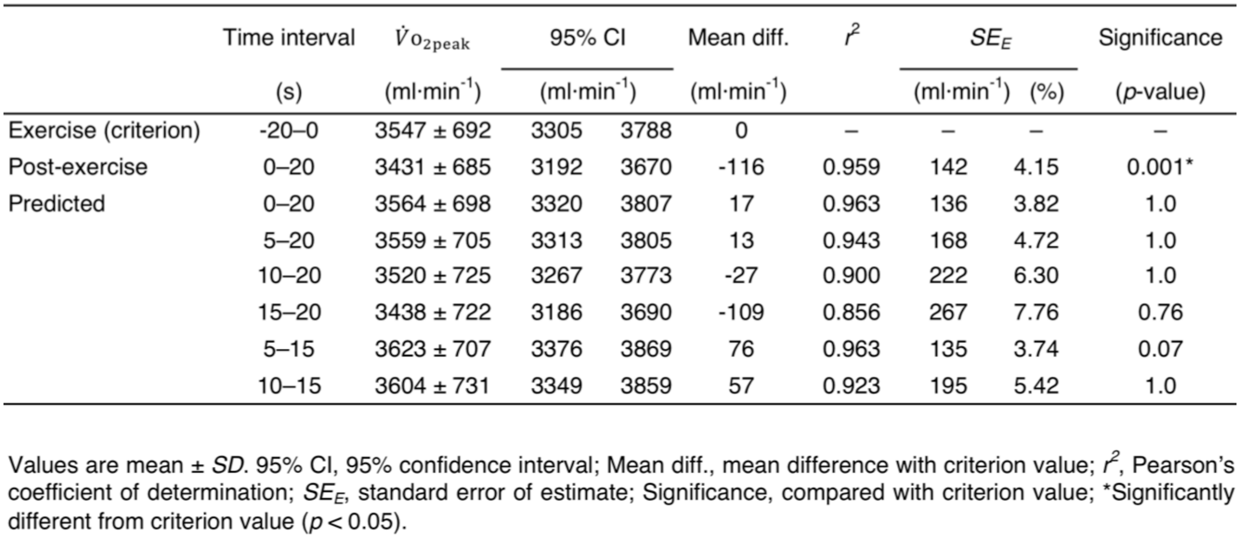


Figure 11. Schematic diagram of $\dot{V}\mathrm{o}_2$ (grey line, average 1-s values for the entire group of swimmers) measured during exercise (shadowed area) and recovery at a 200-m all-out swim. Discontinuous grey lines illustrate time limits (s) in which $\dot{V}\mathrm{o}_2$ values were averaged (black dots, mean ± SD) or where regression was applied. The regression lines (both linear and semilogarithmic) projected on the t_0 of recovery, were used to estimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ using the different BE procedures. Only linear BE regressions are shown here for clarity.

A strong correlation ($r^2 = 0.977$; $p < 0.001$) and nonsignificant differences were found between $\dot{V}\mathrm{o}_{2\mathrm{peak}}(\mathrm{NLR})$ and $\dot{V}\mathrm{o}_{2\mathrm{peak}}(-20-0)$, although $\dot{V}\mathrm{o}_{2\mathrm{peak}}(\mathrm{NLR})$ showed slightly lower values as compared with the criterion (mean Δ = -1.5%; $p = 1.000$). All estimated

$\dot{V}\mathrm{o}_{2\mathrm{peak}}$ values differed from the criterion except BE(20) (p = 0.393), LOG(20) (p = 0.301), and $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$ (p = 1.000). $p\dot{V}\mathrm{o}_2(0-20)$ predicted values showed a good level of agreement, low bias (mean Δ = 1.1%; SE_E = 4.1%), and very strong correlation with criterion values (r^2 = 0.962; $p < 0.001$). The r^2 calculated by cross-validation confirms the robustness of the estimations and the validity of the comparisons (see the summarized results for the different comparisons in table 3).

Table 3. Peak $\dot{V}\mathrm{o}_2$ measured during exercise and peak $\dot{V}\mathrm{o}_2$ values measured and estimated by different procedures during recovery. 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; CV, double cross-validation; SE_E, standard error of estimate; Significance, ANOVA RM and post-hoc Bonferroni when appropriate was used to compare each procedure with the criterion value; *Significantly different from criterion value ($p < 0.05$).



	Time interval (s)	$\dot{V}\mathrm{o}_{2\mathrm{peak}}$ (ml·min^{-1})	95% CI (ml·min^{-1})		Mean diff. (ml·min^{-1})	r^2	SE_E (ml·min^{-1})	SE_E (%)	Significance (p-value)
Exercise (criterion)	-20–0	3547 ± 692	3305	3788	0	–	–	–	–
Post-exercise	0–20	3431 ± 685	3192	3670	-116	0.959	142	4.15	0.001*
Predicted	0–20	3564 ± 698	3320	3807	17	0.963	136	3.82	1.0
	5–20	3559 ± 705	3313	3805	13	0.943	168	4.72	1.0
	10–20	3520 ± 725	3267	3773	-27	0.900	222	6.30	1.0
	15–20	3438 ± 722	3186	3690	-109	0.856	267	7.76	0.76
	5–15	3623 ± 707	3376	3869	76	0.963	135	3.74	0.07
	10–15	3604 ± 731	3349	3859	57	0.923	195	5.42	1.0

Values are mean ± *SD*. 95% CI, 95% confidence interval; Mean diff., mean difference with criterion value; r^2, Pearson's coefficient of determination; SE_E, standard error of estimate; Significance, compared with criterion value; *Significantly different from criterion value ($p < 0.05$).

Postexercise measurements to estimate peak oxygen uptake in 200- and 400-m maximal swims (study III)

As in study II, BE methods overestimated measured values by 7.6% to 13.3% on average, whereas $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$ underestimated measured values by 3.4% (figure 12, table 4), as a consequence of the time-variable delay at the immediate recovery. In series A, none of the estimated values differed from the criterion. However, the best estimations were offered by both modelling procedures, i.e. $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ and $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$, which showed almost perfect correlation with criterion values ($r^2 >$ 0.848), lowest mean differences (mean $\Delta < 1.6\%$), low estimation bias ($SE_E = 7\%$), and good level of agreement, being $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ the procedure that offers a slightly better predictive capacity. Linear BE methods overestimated measured values by 7.6% to 13.3% on average, whereas $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$ underestimated measured values by 3.4%.

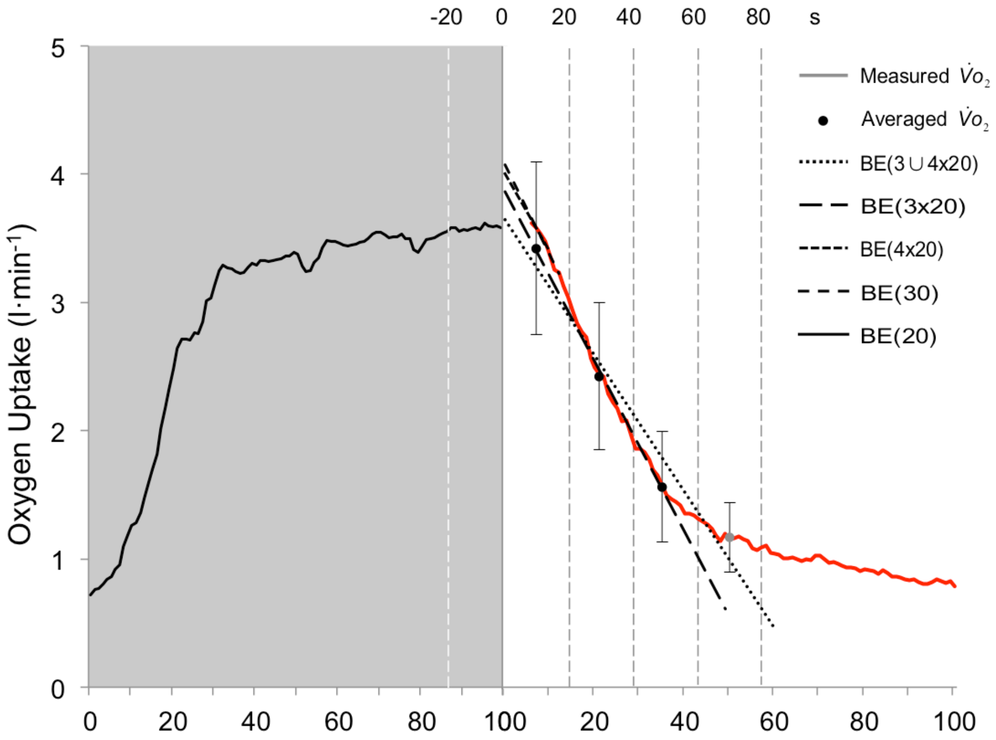


Figure 12. Schematic diagram of $\dot{V}\mathrm{o}_2$ (grey line, average 1-s values for the entire group of swimmers) measured during exercise (shadowed area) and recovery at a 200-m all-out swim (red line). Discontinuous grey lines illustrate time limits (s) in which $\dot{V}\mathrm{o}_2$ values were averaged (black dots, mean ± SD) or where regression was applied. The regression lines (both linear and semilogarithmic) projected on the t_0 of recovery, were used to estimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ using the different BE procedures. Only linear BE regressions are shown here for clarity.

In series B only, BE(30) was different from the criterion and between distances, except $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$, that underestimated the criterion in TT200 and TT400 by -4.5% and -1.3%, respectively, lineal BE procedures overestimated measured $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in both distances. The semilogarithmic BE procedures did no differ with the criterion, except LOG(20) in both distances and LOG(30) in TT200. However, the lowest bias was observed for LOG(20) and LOG(30) at TT200 (mean Δ = 4.7% and 6.1%, respectively), with rest of procedures showing exceedingly large differences with the criterion (mean Δ range = 11.0 to 18.1%) in both TT200 and TT400.

No differences were noted between the criterion $\dot{V}\text{o}_{2\text{peak}}$ values and those estimated using the HR/$\dot{V}\text{o}_2$ modelling procedure with slightly lower bias and better predictive capacity shown by $p\dot{V}\text{o}_{2\text{peak}}(5-20)$ (mean Δ = 0.1% and 1.6% for TT200 and TT400, respectively), compared with $p\dot{V}\text{o}_{2\text{peak}}(0-20)$ (table 4).

Table 4. Peak $\dot{V}\text{o}_2$ measured during exercise (200SS) and estimated from postexercise measurements by the HR/$\dot{V}\text{o}_2$ modelling procedure following the same test (SS200) and after a 400-m unimpeded swim (TT400).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).

Procedure	Test (m)	Peak $\dot{V}\text{o}_2$ (ml·min^{-1})	95% CI (ml·min^{-1})		Mean diff. (ml·min^{-1})	Mean diff. (%)	r^2	SE_E (ml·min^{-1})	SE_E (%)	Diff. with criterion# (*p*)	Diff. between tests# (*p*)
$\dot{V}\text{o}_{2\text{peak}}(-20-0)$ (criterion)	200	3192 ± 667	2850	3535	-	-	-	-		-	
$p\dot{V}\text{o}_{2\text{peak}}(0-20)$	200	3217 ± 691	2861	3572	24	0.7	0.861	257	8.0	1.000	0.373
	400	3303 ± 694	2946	3659	110	3.3	0.747	346	10.9	1.000	
$p\dot{V}\text{o}_{2\text{peak}}(5-20)$	200	3194 ± 706	2831	3557	2	0.1	0.809	301	9.4	1.000	0.620
	400	3245 ± 651	2911	3580	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).

DISCUSSION

To assess the validity of a new model based on HR and $\dot{V}\mathrm{o}_2$ off-kinetics for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in swimming, in **study I**, we first compared directly measured values with those predicted by the model, at different time intervals, and estimated from a single 20-s recovery measurement. Then (**study II**), we compared directly measured $\dot{V}\mathrm{o}_2$ during a 200-m all-out test with that estimated by postexercise procedures during recovery in the same 200-m maximal test (SS200). Finally (**study III**), we first compared (series A) directly measured $\dot{V}\mathrm{o}_2$ during a 200-m all-out swim (SS200) with that estimated by commonly used postexercise procedures on a separate swim over the same distance where the swimmers performed completely unimpeded (TT200). Then (series B), we compared directly measured $\dot{V}\mathrm{o}_2$ during a 200-m all-out with that estimated by postexercise procedures during recovery in the same 200-m maximal test (SS200) and with that estimated by commonly used postexercise procedures on a separate unimpeded swim over the same distance (TT200) and over 400 m (TT400).

The main findings were: 1) the HR-$\dot{V}\mathrm{o}_2$ modelling technique, based on continuous beat-to-beat HR and postexercise bxb $\dot{V}\mathrm{o}_2$ measurements during 20 s has shown to be the most valid and accurate procedure for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in competitive swimmers, overcoming the bias imposed by other procedures and the limitations imposed by the equipment during direct measurements; 2) $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ can be estimated from some (but not all), postexercise procedures with good accuracy after an all-out middle-distance swim (200 and 400 m) even when a time gap between the cessation of exercise and the first $\dot{V}\mathrm{o}_2$ measurement occurs; 3) both an all-out 200-m or 400-m all-out swims are valid tests for assessing swimming-specific $\dot{V}\mathrm{o}_{2\mathrm{max}}$ during all unimpeded free swimming when combined with HR and postexercise $\dot{V}\mathrm{o}_2$ measurements and the novel modelling technique.

Performance during $\dot{V}o_2$ assessments

Using postexercise measurement to estimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in swimming gives the advantage of allowing the athletes to swim completely unimpeded (i.e. without mouthpiece, snorkel, and tubing) and, hence, enabling them to attain maximal effort without any modification, whatsoever, of swimming technique and hydrodynamics (i.e. stroke kinematics, breathing pattern, diving starts and turns and subsequent underwater gliding phase, and body position and drag (Keskinen et al. 2001; Kjendlie et al. 2003; Kapus et al. 2006; Barbosa et al. 2010a) which result in lower swimming speeds. In this sense, mean differences of ~10% in maximal speed were found during a multistage continuous test (Keskinen et al. 2001), and in maximal speed at $\dot{V}\mathrm{o}_{2\mathrm{max}}$ (Montpetit et al. 1981). The maximal speed attained in 100-m (Barbosa et al. 2010a) or 400-m all-out tests (Lavoie et al. 1983) is also faster when swimming unimpeded (~13-16% and ~5-6%, respectively), the disparity being explained by the longer distance and the subsequent cumulative effect of altered conditions along the swim.

Backward extrapolation methods

Regarding the classical lineal BE techniques (i.e. extrapolation to t_0 of the recovery of average values obtained during 60 to 80 s), they all yielded larger bias for 200-m swim with uninterrupted measurements in **study II** (mean Δ range = 6.2 to 7.6%), in a separated test (TT200) in **study III** series A (mean Δ range = 4.2% to 7.2%), and in TT400 in series B (mean Δ range = 7.2% to 13.9%). Even larger bias was observed in semilogarithmic BE estimations in a 200-m maximal swim in study II (mean Δ range = 15.4% to 17.9%), and in times trials in **study III** (mean Δ range = 13.9% to 18.1%, and 14.1% to 16.8% for TT200 and TT400, respectively), making them useless for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ values during swimming. Lavoie et al. reported a similar overestimation (~20%) when using the semilogarithmic BE method comparable to LOG(3∪4x20) after a maximal 400-m swim, and attributed this substantial discrepancy to a time delay in the $\dot{V}\mathrm{o}_2$ recovery curve (Lavoie et al. 1983).

The delay phenomenon was first reported by di Prampero et al. who observed that, contrary to steady state aerobic exercise, $\dot{V}\mathrm{o}_2$ remains practically at exercise levels for about 12-35 s after cessation of supramaximal leg-cycling exercise of very short duration (11-51 s) (Di Prampero et al. 1973), and was later corroborated for 1-min all-out cycling exercise and quantified in 5-10 s (Tural et al. 2014). An indirect proof is offered by the work of Costill et al. who observed a close correlation between post exercise 20-s $\dot{V}\mathrm{o}_2$ values and $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ (r^2=0.96), with a relatively small mean difference (~6%), but decreasing correlation during subsequent recovery periods (20-40 s, r^2 = 0.94; 40-60 s, r^2 = 0.52; 60-80 s, r^2= 0.59) (Costill et al. 1985b). Later, using bxb equipment, Rodríguez confirmed the existence of a time delay after an all-out 400-m swimming exercise of about 3-10 s at the onset of the $\dot{V}\mathrm{o}_2$ recovery curve in competitive swimmers (Rodríguez 1997; 1999). Similar time delay was observed after an all-out 100-m swim (~14 s) (Rodríguez et al. 2016), by Sousa et al. at a square-wave maximal swim at 100% of $\dot{V}o_{2\max}$ using a double-exponential function (~11 s) (Sousa et al. 2015) and by Chaverri et al. at a 200-m supramaximal swim (9.1 ± 4.8 s) (Chaverri et al. 2016a) (**study I**).

Therefore, these results corroborate that the overestimation observed when BE of 20 to 80 s values are used to predict $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ during supramaximal exercise is caused by the time delay during the immediate recovery being that: 1) as evidenced in figure 3, there is slower decay of the $\dot{V}\mathrm{o}_2$ curve at the onset of the recovery period; 2) visual inspection of each $\dot{V}\mathrm{o}_2$ curves confirmed a time-variable delay in most swimmers (9.1 ± 4.8 s in **study II**); 3) underestimation of criterion values was observed when $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was calculated using 20-s sampling averages (i.e. $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$), whereas systematic overestimation was noted for the rest all BE calculation methods; 4) the largest overestimation was yielded by semilogarithmic BE, which might probably introduce an error derived from the mathematical transformation of the monoexponential regression of the fast component of the $\dot{V}\mathrm{o}_2$ recovery curve into a linear function; and 5) the better estimations when $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was calculated using 20-s sampling averages whereas bias increase in all BE methods when longer sampling times were used.

Mathematical modelling

As explained in **study I**, the mathematical model relies on the Fick's principle (eq. 2 and 3) with two basic assumptions. First, that SV remains nearly constant during the first seconds of recovery (eq. 4). In this sense, during the recovery of light to moderate exercise, SV does not fall as rapidly as HR does and remains above exercise levels (Eriksen et al. 1990) for as long as 3 to 5 min (Miyamoto et al. 1983; Eriksen et al. 1990; Takahashi et al. 2005), especially in the upright position (Takahashi et al. 2005). Sustained high $\dot{Q}$ during the recovery phase was also demonstrated, explaining the on-/off-transient $\dot{V}\mathrm{o}_2$ kinetics asymmetry (i.e. slower off-transient time constant, also confirmed in 200-m maximal swimming (Sousa et al. 2011a)), appearing to be a result of both SV and HR being maintained to ensure a sufficiently high O_2 flow to the muscles during recovery at a time when muscle $\dot{V}\mathrm{o}_2$ remains high (Yoshida et al. 1994).

Therefore, the decrease in $\dot{Q}$ (and consequently $\dot{V}\mathrm{o}_2$) would occur mainly by decreased post-exercise HR. Sheldahl et al. suggested that the central redistribution of blood volume with head-out water immersion cycling exercise at 40, 60 and 80% of $\dot{V}\mathrm{o}_{2\mathrm{max}}$, leading to an increase in SV without a proportional decrease in HR, evidences that $\dot{Q}$ is regulated at a higher level during upright exercise in water compared with that on land (Sheldahl et al. 1987). Although there is no available evidence that this response pattern takes place during maximal exercise, in line with these reports, some of our subjects showed a little rise in $\dot{V}\mathrm{o}_2$ while HR remained constant immediately after the cessation of exercise, which can be loosely interpreted as a rise in SV. This rise could also be explained by the change in body position from horizontal to vertical; the lower part of the body is now deep immersed and under a hydrostatic pressure gradient, which would translocate blood from the lower limbs and abdomen into the thoracic region, thus increasing venous return and SV compared to the horizontal position (Arborelius et al. 1972).

The second assumption of the mathematical model is that $C(a-\bar{v})\mathrm{o}_2$ remains nearly constant during the first seconds of recovery. This assumption relies on the fact that a certain venous volume with constant O_2 saturation can be assumed to occur during the immediate recovery while arterial saturation is constant. Because of the distance between muscle and mouth, substantial changes in $C(a-\bar{v})\mathrm{o}_2$ over the first seconds of recovery are not to be expected (Drescher et al. 2010).

As shown in figure 10, $p\dot{V}\mathrm{o}_2$values do not decline over the first 20 s after the cessation of exercise, which is likely the time for the onset of changes in $C(a-\bar{v})\mathrm{o}_2$ perceivable in the exhaled air. Moreover, in **study I**, the $\dot{V}\mathrm{o}_2$ off-kinetics are virtually parallel to HR off-kinetics during the first 20 s of recovery, suggesting that no substantial changes in $C(a-\bar{v})\mathrm{o}_2$ and SV occurred within this time period. Therefore, it seems justified to use HR on- and off-kinetics as a proxy of $\dot{V}\mathrm{o}_2$ dynamic response during the early recovery On the other hand, the high correlation and the low mean difference between $\dot{V}\mathrm{o}_2$ during exercise and $p\dot{V}\mathrm{o}_2(0-20)$ in **studies I, II** and **II**, strengthen the validity of the physiological assumptions of the model.

In **study I**, the best end-exercise $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ estimates were provided by $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$, i.e. values modelled during the first 20 s of the recovery ($r^2 = 0.963$; mean $\Delta = 0.5\%$; $SE_E = 3.8\%$). In **study II**, using the same HR-$\dot{V}\mathrm{o}_2$ modelling procedure, the present study corroborates its validity and accuracy, as almost identical results were obtained ($r^2 = 0.962$; mean $\Delta = 1.1\%$; $SE_E = 4.1\%$) (table 3).

On the other hand, the **study III** showed that, when $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was estimated after an unimpeded swims, the most accurate estimations of exercise $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ without significant bias were provided by $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ (mean Δ range = 1.3%, and 0.1% (TT200) and 1.6% (TT400) in this **study III** (table 4).

Assessing maximal aerobic power in swimming

Another key issue is which distance can be considered most appropriate to assess maximal aerobic power in swimmers, and whether $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ at supramaximal middle distance tests can be considered as the swimmers' true $\dot{V}\mathrm{o}_{2\mathrm{max}}$. As opposed to multistage incremental tests, e.g. 3.7x200 m (see (Sousa et al. 2014a) for a review), single-distance all-out tests enable the swimmers to attain race speeds provided they can swim fully unimpeded. To date, 200-m swims have been widely adopted in studies with competitive swimmers for testing purposes (Reis et al. 2010b; Sousa et al. 2010; Figueiredo et al. 2011; Sousa et al. 2011a; Fernandes et al. 2012; Rodríguez et al. 2015; Chaverri et al. 2016a; Chaverri et al. 2016b) because of the intense activation of both the aerobic and anaerobic energy metabolism (Rodríguez and Mader 2011) and its average duration (~2-2.5 min on average), sufficient to elicit $\dot{V}\mathrm{o}_{2\mathrm{max}}$ in most cases (Morgan et al. 1989; Rossiter et al. 2006). It is possible that shorter or longer distances could limit its attainment, although the extremely fast $\dot{V}\mathrm{o}_2$ kinetics of swimmers, as discussed below. In the **study III**, no differences were noted between $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ at TT200 and TT400 (3194 ± 706 vs. 3245 ± 651; *p* = 0.62), which suggests that both distances yield the same $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in competitive swimmers.

Concerning the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ vs. $\dot{V}\mathrm{o}_{2\mathrm{max}}$ controversy, not restricted to swimming, Holmér compared $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ measured using the Douglas bag method in a swimming flume, with that obtained during laboratory running and cycling, and reported higher $\dot{V}o_{2\text{peak}}$ in running than in swimming; these results were related to the expertise in swimming, since the mean Δ was lower in elite swimmers (4.2%) compared to non swimmers group (20%) (Holmér 1972). Rodríguez, instead, using a bxb gas analyser in a group of competitive swimmers, observed no differences in $\dot{V}\mathrm{o}_{2\text{peak}}$ when comparing postexercise measurements after a 400-m maximal swim and obtained during laboratory cycling and running, and concluded that a maximal 400-m swim is a valid test for $\dot{V}\mathrm{o}_{2\max}$ determination (Rodríguez 2000). Moreover, the same author reported that a group of swimmers that had reached their $\dot{V}\mathrm{o}_{2\max}$ during an incremental 5x400-m test attained ~95% of $\dot{V}\mathrm{o}_{2\max}$ during an all-out 100-m swim (Rodríguez 1999). In line with previous results, Chaverri et al. did not find differences in $\dot{V}\mathrm{o}_{2\text{peak}}$ reached at three swimming distances (50, 100 or 200, and 400 m) swum at maximal speed (Chaverri et al. 2014). This phenomenon is most likely explained by the very fast $\dot{V}\mathrm{o}_2$ on-kinetics within the extreme intensity domain exhibited by competitive swimmers, exemplified by time constant (τ) mean values of 9 s in 100-m (Rodríguez et al. 2016), 11 s in 200 m (Sousa et al. 2011a; Sousa et al. 2011b; Rodríguez et al. 2015), and 17 s (when corrected using the same biexponential model) in 400 m all-out swims (Rodríguez et al. 2003a). This very fast $\dot{V}\mathrm{o}_2$ on-kinetics, among the fastest in the literature, is likely produced by an intense activation of lower limbs and trunk muscles during kicking in the faster swims (Rodríguez et al. 2016). Globally, these observations suggest that a 200-m all-out swim yields maximum $\dot{V}\mathrm{o}_2$ values and, hence, it can be considered a valid and practical test to determine maximal aerobic power during swimming using postexercise measurements in competitive swimmers.

Finally, although we do not anticipate large discrepancies, since this study involved elite swimmers only, it seems of interest to investigate swimmers of lower competitive level and, especially, of younger age.

CONCLUSIONS

Using technologically advanced respiratory equipment at the poolside has improved the feasibility and validity of gas exchange assessment in swimming. Specifically designed snorkels, despite the advantage of allowing continuous measurements during exercise and recovery, still face limitations such as precluding diving starts and flip turns, altering stroke kinematics, modifying the breathing pattern, and causing a sometimes unbearable discomfort. Instead, using postexercise $\dot{V}\mathrm{o}_2$ measurement enables the swimmers to exercise without being hindered by the respiratory equipment, to exploit their maximal potential, and to reach race speed. However, measurement accuracy is key to postexercise gas exchange assessment in pool conditions. From the present investigation, in which directly measured $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ over 200 and 400-m distances at maximal speed was compared with estimations from postexercise measurements according to various commonly adopted procedures in elite swimmers, we derive the following conclusions:

1. We propose a new model based on continuous beat-to-beat HR and postexercise breath-by-breath $\dot{V}\mathrm{o}_2$ measurements during 20 s, as a feasible, valid and accurate procedure for estimating $\dot{V}o_{2\mathrm{peak}}$ in competitive swimmers. This method, based on the Fick's principle under certain physiological assumptions, avoids the bias of $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ estimations incurred by using backward extrapolation methods and overcomes the constraints imposed by respiratory equipment during swimming.

2. The large overestimation exhibited by the classical backward extrapolation

methods (~4-20%) can be explained by a time-variable delay of the fast component of the $\dot{V}o_2$ off-kinetics response (~10 s on average). Backward extrapolation methods using linear and semilogarithmic regression of shorter measurement periods (0-20 s) provided more accurate results, but still overestimated $\dot{V}o_{2\text{peak}}$ by ~2-3%, respectively.

3. Considering that the swimmers typically vary their individual performance in the range of ~3% across the competitive season, the large bias exhibited by the BE techniques (linear and semilogarithmic) largely compromises their ability to monitor progress in elite swimmers.

4. The widely adopted 20-s average method underestimates $\dot{V}o_{2\text{peak}}$ by ~3-5% because of the rapid decay of $\dot{V}o_2$ during the immediate recovery (off-kinetics fast component).

5. The new HR-$\dot{V}o_2$ modelling technique accurately estimates $\dot{V}o_{2\text{peak}}$ in competitive swimmers without significant bias (0.1-1.6%) after all-out middle-distance swims (200 and 400 m), even when a time gap between the cessation of exercise and the first $\dot{V}o_2$ measurement occurs.

6. Both 200- and 400-m all-out swims combined with HR and postexercise $\dot{V}o_2$ measurements yielded equal $\dot{V}o_{2\text{peak}}$ values, thus confirming that they are valid tests for assessing swimming-specific $\dot{V}o_{2\text{max}}$, according to previous research.

7. Therefore, the new HR/$\dot{V}o_2$ modelling technique appears as the method of choice

for assessing cardiorespiratory and metabolic fitness in competitive swimmers when postexercise measurements are chosen to avoid the burden of respiratory equipment during swimming exercise.

FUTURE PERSPECTIVES

The methodological advance offered by the novel modelling methodology opens new research and sport-applied perspectives. First, since it enables to estimate $\dot{V}\text{o}_{2\text{peak}}$ at race speeds with good accuracy, it will allow measuring this important parameter at different distances and intensity domains. However, this goal will be better achieved if the present results were confirmed also at submaximal speeds. Since previous studies using BE methods showed, if anything, better results compared with maximal swimming (Costill et al. 1985b), probably because of the lower influence of the time delay of the $\dot{V}\text{o}_2$ recovery curve, assessing the accuracy of the new modelling technique during submaximal swimming are required. Unpublished results from our group (to be submitted) confirm that the technique predict $\dot{V}\text{o}_{2\text{peak}}$ at submaximal speeds with similar accuracy. If this can be confirmed, the measurements of key variables for swimming assessment, such as swimming economy and efficiency at different speeds and distances, relationship between metabolic and biomechanical parameters (e.g. compared efficiency using different swimming techniques, racing suits, or environmental conditions), would be more feasible, accurate, and ecologically valid.

Testing and monitoring competitive swimmers can also benefit from the new methodology. Using respiratory equipment is a very complex and cumbersome procedure for the scientist or coach and is not well accepted by the swimmers. Conversely, postexercise measurements are much easier to perform and well tolerated by the swimmers, who can swim fully unimpeded and being asked just to breath into a mask face after the swim. HR measurement implies wearing a chest band, which is something most swimmers are used to. Therefore, we anticipate more specific testing procedures (e.g. true maximal speeds swum with unaltered technique) that can be used more frequently with lower expense and burden.

A development in which we started to work some years ago is the combination of testing procedures (e.g. $\dot{V}\mathrm{O}_{2\mathrm{peak}}$, blood lactate, kinematical parameters) with computer simulation of muscle metabolism (Mader et al. 1983; Mader 2003; Rodríguez and Mader 2003b; 2011) to improve the characterization of individual metabolic capacities, and to simulate different conditions in their physiological response to exercise. The new technique has an effect of the accuracy of these measurements and, thus, in the acquisition of physiological individual data in which the computer simulation is based.

Finally, it is of interest to confirm the present results in populations different from competitive elite swimmers, such as younger (junior and age-group swimmers), older (master swimmers), and recreational swimmers.

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Study I

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Human Kinetics
ORIGINAL INVESTIGATION

A New Model for Estimating Peak Oxygen Uptake Based on Postexercise Measurements in Swimming

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Purpose: Assessing cardiopulmonary function during swimming is a complex and cumbersome procedure. Backward extrapolation is often used to predict peak oxygen uptake ($\dot{V}O_{2peak}$) during unimpeded swimming, but error can derive from a delay at the onset of $\dot{V}O_2$ recovery. The authors assessed the validity of a mathematical model based on heart rate (HR) and postexercise $\dot{V}O_2$ kinetics for the estimation of $\dot{V}O_{2peak}$ during exercise. ***Methods:*** 34 elite swimmers performed a maximal front-crawl 200-m swim. $\dot{V}O_2$ was measured breath by breath and HR from beat-to-beat intervals. Data were time-aligned and 1-s-interpolated. Exercise $\dot{V}O_{2peak}$ was the average of the last 20 s of exercise. Postexercise $\dot{V}O_2$ was the first 20-s average during the immediate recovery. Predicted $\dot{V}O_2$ values (p$\dot{V}O_2$) were computed using the equation: $p\dot{V}O_2(t) = \dot{V}O_2(t)\ HR_{\text{end-exercise}}/HR(t)$. Average values were calculated for different time intervals and compared with measured exercise $\dot{V}O_{2peak}$. ***Results:*** Postexercise $\dot{V}O_2$ (0–20 s) underestimated $\dot{V}O_{2peak}$ by 3.3% (95% CI = 9.8% underestimation to 3.2% overestimation, mean difference = –116 mL/min, SE_E = 4.2%, P = .001). The best $\dot{V}O_{2peak}$ estimates were offered by p$\dot{V}O_{2peak}$ from 0 to 20 s (r^2 = .96, mean difference = 17 mL/min, SE_E = 3.8%). ***Conclusions:*** The high correlation (r^2 = .86–.96) and agreement between exercise and predicted $\dot{V}O_2$ support the validity of the model, which provides accurate $\dot{V}O_{2peak}$ estimations after a single maximal swim while avoiding the error of backward extrapolation and allowing the subject to swim completely unimpeded.

Keywords: $\dot{V}O_{2max}$, oxygen kinetics, backward extrapolation, modeling, heart rate

The assessment of cardiopulmonary gas exchange and oxygen uptake ($\dot{V}O_2$) in swimming is a complex and cumbersome procedure and still faces limitations imposed by the water environment and the equipment (see Sousa et al[1] for a review). Specifically, in-water measurements require breathing through a snorkel connected with a system of tubes and built-in valves that allows collecting the expired gases while keeping the inspiratory and expiratory tubes, as well as the analyzers, dry. From a technical standpoint, 2 main indirect calorimetric approaches have been used to collect and analyze expiratory gases in swimming: (1) measurements during exercise using snorkels with built-in valves connected to Douglas bags,[2–4] open-circuit metabolic carts,[5,6] or breath-by-breath portable gas analyzers[7] and (2) postexercise measurements with gas collection via facemask or mouthpiece connected to Douglas bags[8] or open-circuit metabolic carts.[9]

To enable continuous measurements in the field, portable gas analyzers are now preferred by many investigators because of their more advantageous sampling capability, practicality, and acceptable level of accuracy.[7,10] However, the inability of swimmers to execute diving starts and underwater gliding after starts and turns, which play a major role in the overall swimming performance, also impairs the ecological validity of $\dot{V}O_2$ measurements. Even if these constraints do not prevent the investigation of many aspects of the physiological response during swimming, 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, all-out 100-m front crawl and breaststroke swims were ~5% to 6% slower when using a snorkel than during unimpeded swimming.[11] An alternative procedure to during-swimming measures is the backward extrapolation of the O_2 recovery curve, first described by Di Prampero et al[12] and validated by Léger et al.[13] Montpetit et al[8] compared $\dot{V}O_{2peak}$ values obtained using the Douglas-bag technique in a multistage free-swimming test with those predicted using the backward-extrapolation method (ie, recovery from the same swimming test), as well as with those measured during an uphill treadmill running test. Despite finding good method agreement, they concluded that, to ensure the validity of the method, short-duration exercises (<5 min) and supramaximal intensities should be avoided, as a delay in the onset of O_2 recovery may appear. Another approach was used by Costill et al,[14] who showed good agreement between $\dot{V}O_{2peak}$ during maximal and submaximal swimming and a single 20-second expired-gas collection taken immediately after a 4- to 7-minute swim. However, breath-by-breath postexercise measurements confirmed the occurrence of a delay at the onset of the $\dot{V}O_2$ recovery curve and identified a plateau in many—but not all—swimmers, suggesting this to be the main source of error in these 2 estimation procedures.[9,15]

To overcome these limitations and to improve the estimation of $\dot{V}O_{2peak}$ from postexercise measurements, our group recently proposed a mathematical model based on heart rate (HR) and off-transient $\dot{V}O_2$ kinetics.[16] In short, based on the Fick principle, the model calculates a predicted $\dot{V}O_2$ at a given time of 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.[17]

The aim of the current study was to assess the validity of this model by comparing direct $\dot{V}O_{2peak}$ measurements during the final period of swimming exercise (reference method) with those predicted by the model, as well as those indirectly estimated from a single 20-second measurement during recovery.[14] Furthermore, we

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investigated different recovery intervals in an attempt to enhance the accuracy of $\dot{V}O_{2peak}$ estimation using the model.

Methods

Subjects

Thirty-four elite swimmers, all members of national and Olympic teams, including 18 women (mean ± SD age 20.8 ± 3.5 y, height 173.2 ± 5.8 cm, body mass 64.5 ± 5.6 kg) and 16 men (age 22.7 ± 3.6 y, height 186.8 ± 6.0 cm, body mass 80.8 ± 7.7 kg), voluntarily participated in this study. Informed consent was obtained from all participants included in the study and their legal guardians when appropriate. The study received approval from the Ethics Committee for Clinical Sport Research of Catalonia in accordance of the 1964 Helsinki Declaration and its later amendments.

Design

All tests were conducted in a 50-m indoor pool (temperature: water 26–27°C, air 27–28°C). After an ~30-minute swimming-based warm-up followed by 10 minutes of passive recovery at poolside, participants completed an all-out 200-m front-crawl swim to determine exercise $\dot{V}O_{2peak}$. After exercise, the swimmers remained in an upright position immersed up to the sternum. In-water starts and touched open turns with no underwater gliding were performed.

Methodology

$\dot{V}O_2$ was measured using a telemetric portable gas analyzer (K4 b^2, Cosmed, Italy) held over the head of each swimmer by an assistant following him or her along the pool. The equipment was connected to the swimmer by a low hydrodynamic-resistance respiratory snorkel-and-valve system, previously validated both in vivo[18] and using a gas-exchange simulator.[19] The gas analyzers were calibrated before each test with gases of known concentration (16% O_2, 5% CO_2), and the turbine volume transducer was calibrated using a 3-L syringe according to the manufacturer's instructions. Pulmonary gas exchanges were measured breath by breath 1 minute before, during, and 3 minutes postexercise. HR was continuously measured using waterproof beat-to-beat monitors (CardioSwim, Freelap, Switzerland).

$\dot{V}O_2$ and HR data were time-aligned to the start of the measurements, 1-second interpolated, and plotted against time. Two $\dot{V}O_{2peak}$ values were identified (Figure 1): End-exercise $\dot{V}O_{2peak}$ was the average value over the last 20 seconds of exercise[20] and was taken as the reference value (criterion) for all comparisons, and postexercise $\dot{V}O_2$ was the average value over the first 20 seconds of the recovery period ($\dot{V}O_2$ [0–20]). The 20-second duration of the end- and postexercise measurements was chosen for the following reasons: (1) to ensure that only last swimming-lap data were used, as $\dot{V}O_2$ usually decreases during the turns; (2) to minimize the influence of interbreath fluctuations (ie, improvement of signal-to-noise ratio); (3) to prevent too high $\dot{V}O_{2max}$ values frequently obtained when using shorter time intervals[21]; (4) to maintain end- and postexercise temporal equality, as previous results during 200-m maximal swimming showed an on/off symmetry in the $\dot{V}O_2$ kinetic response[22]; and (5) previous work showed that 20-second average values produced the same $\dot{V}O_{2peak}$ as the total amplitude of the monoexponential equation fitting the $\dot{V}O_2$ on-kinetics during 200-m maximal swims.[20]

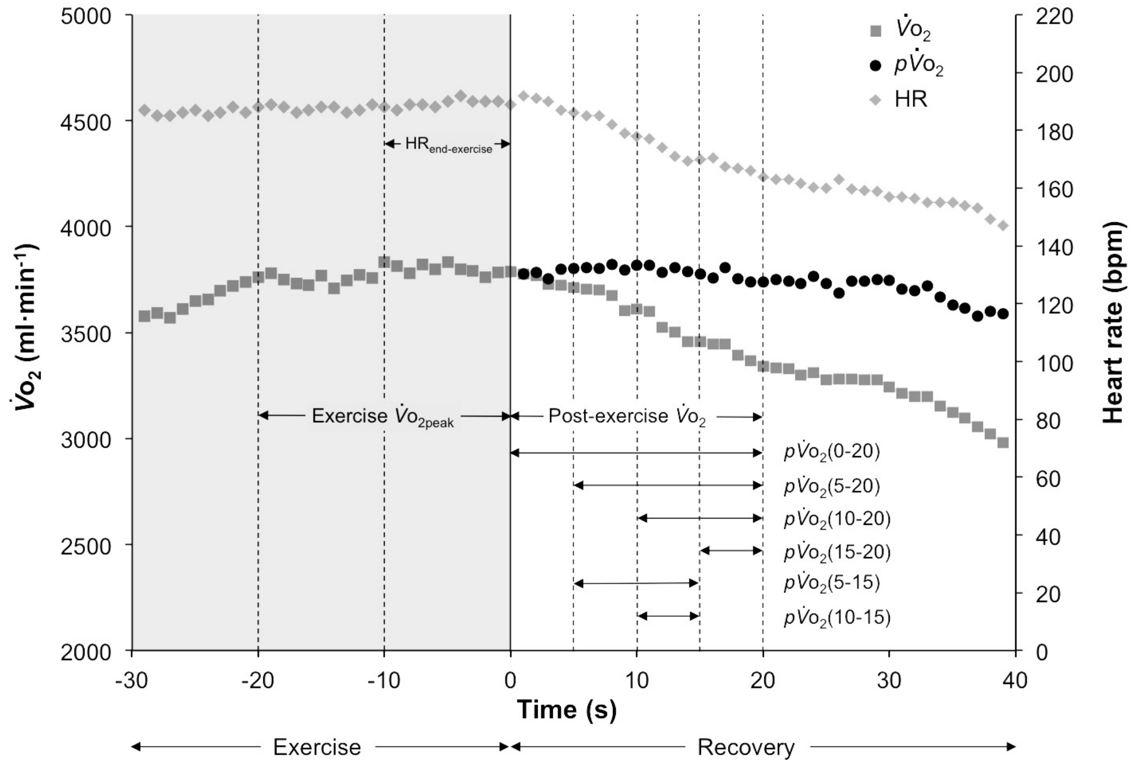

Figure 1 — Heart-rate (HR) (diamonds) and oxygen-uptake ($\dot{V}O_2$) (squares) kinetics over the last 30 seconds of exercise and immediate recovery during a 200-m maximal swim in 1 swimmer. Vertical lines indicate time intervals during exercise ($t < 0$) and recovery ($t > 0$). The black circles indicate modeled (predicted) values ($p\dot{V}O_2$) during recovery. Short dashed lines indicate different time intervals used for comparisons.

The rationale of the proposed new model relies on the Fick principle relating cardiac output ($\dot{Q}$) with $\dot{V}O_2$ and arteriovenous O_2 difference, $C(a-\bar{v})O_2$, according to the equation

$$\dot{V}O_2 = \dot{Q} \cdot C(a-\bar{v})O_2 \qquad \text{(Eq 1)}$$

On the other hand, $\dot{Q}$ equals the cardiac stroke volume (SV) times the HR:

$$\dot{Q} = \text{SV} \cdot \text{HR} \qquad \text{(Eq 2)}$$

Under the assumption that SV does not significantly change over the first seconds of recovery,[23] changes in HR can be considered a proxy for changes in $\dot{Q}$, and, likewise, the $\dot{V}O_2$:HR ratio can be used a proxy of the arteriovenous O_2 difference:

$$\frac{\dot{V}O_2}{\text{HR}} \approx C(a-\bar{v})O_2 \cdot \text{constant} \qquad \text{(Eq 3)}$$

Based on these 2 assumptions, the wmathematical model computes "predicted" $\dot{V}O_2$ values (p$\dot{V}O_2$) based on synchronized postexercise $\dot{V}O_2$ and HR measurements (Eq 3) and HR at the end of exercise. Thus, at a given time *t* during the recovery period, p$\dot{V}O_2$ can be calculated according to the equation

$$p\dot{V}O_2(t) = \frac{\dot{V}O_2(t)}{\text{HR}(t)} \text{HR}_{\text{end-exercise}} \qquad \text{(Eq 4)}$$

where p$\dot{V}O_2(t)$ is the predicted (modeled) postexercise $\dot{V}O_2$ at time *t*, $\dot{V}O_2(t)$ is the postexercise 1-second-interpolated $\dot{V}O_2$ at time *t*, HR(*t*) is the postexercise 1-second-interpolated HR value at time *t*, and $\text{HR}_{\text{end-exercise}}$ is the highest value of the last 10-second average HR at the end of exercise (excluding single peaks more than 5 beats/min higher than the rest, corresponding to ~1 SD from mean HR during the last 10 s of exercise).

In an attempt to enhance the accuracy of the estimation, $\dot{V}O_{2\text{peak}}$ was compared with p$\dot{V}O_2$ at different time intervals (*t* = 0–20, 5–20, 10–20, 15–20, 5–15, and 10–15 s), which were expressed as p$\dot{V}O_2$(0–20), p$\dot{V}O_2$(5–20), p$\dot{V}O_2$(10–20), p$\dot{V}O_2$(15–20), p$\dot{V}O_2$(5–15), and p$\dot{V}O_2$(10–15).

Statistical Analysis

Descriptive data are presented as mean ± SD and mean difference. Normality of distributions and homogeneity of variances were verified using Shapiro-Wilk and Levene tests, respectively. A 1-way analysis of variance with repeated measures (RM-ANOVA) and post hoc Tukey test if appropriate were used for multiple comparisons between $\dot{V}O_{2\text{peak}}$ (criterion value) and each of the postexercise measured and predicted values. The Pearson coefficient of determination (r^2) was used to assess correlation between variables. Mean difference plots[24] were used to assess agreement between measured and predicted values. The level of significance was set at $P < .05$. Statistical analyses were conducted using SPSS 15.0 (SPSS Inc, Chicago, IL, USA).

Results

Figure 1 shows an example of HR and $\dot{V}O_2$ over the last 30 seconds of the exercise and the immediate recovery, as well as the p$\dot{V}O_2$ values for different postexercise intervals in 1 participant. In accordance with previous results,[22,25] no evidence of a slow component was observed in any swimmer as exercise duration constrained the appearance of phase III of the $\dot{V}O_2$ kinetics.[26]

Table 1 summarizes the comparisons between $\dot{V}O_{2\text{peak}}$ measured during exercise and postexercise measured and predicted values at different time intervals. End-exercise $\dot{V}O_{2\text{peak}}$ (criterion value) was 3.3% higher than postexercise $\dot{V}O_2$(0–20). All predicted p$\dot{V}O_2$s were highly correlated with (r^2 = .86–.96) and were not different from the criterion value (P > .76–1.0). The best estimate (ie, lowest bias) of exercise $\dot{V}O_{2\text{peak}}$ was offered by p$\dot{V}O_2$(0–20) (r^2 = .96, mean difference = 17 mL/min, SE_E = 3.8%) and p$\dot{V}O_2$(5–20) (r^2 = .94, mean difference = 13 mL/min, SE_E = 4.7%).

Figure 2 provides Bland-Altman difference plots showing good agreement between exercise $\dot{V}O_{2\text{peak}}$ and predicted recovery p$\dot{V}O_2$(0–20) and p$\dot{V}O_2$(5–20) data.

Discussion

Our main finding was that the proposed mathematical model based on HR kinetics and postexercise $\dot{V}O_2$ measurements in a maximal 200-m swim is a valid procedure of estimating $\dot{V}O_{2\text{peak}}$ in competitive swimmers, with optimal predictive capacity if based on measurements obtained within 20 seconds after the cessation of exercise. We also found that assessing $\dot{V}O_{2\text{peak}}$ by using a single 20-second measurement during recovery as proposed by Costill

Table 1 Oxygen-Uptake ($\dot{V}O_2$) Measurements During Exercise (Criterion Value) and Recovery (Postexercise) and $\dot{V}O_2$ Predicted by the Model at Different Time Intervals

	Time interval (s)	$\dot{V}O_2$ (mL/min)	95% CI (mL/min)	Mean difference[a] (mL/min)	r^2	SE_E		P[a]
						mL/min	(%)	
Exercise (criterion)	–20 to 0	3547 ± 692	3305–3788	0	—	—	—	—
Postexercise	0–20	3431 ± 685	3192–3670	–116	.959	142	4.15	.001*
Predicted	0–20	3564 ± 698	3320–3807	17	.963	136	3.82	1.0
	5–20	3559 ± 705	3313–3805	13	.943	168	4.72	1.0
	10–20	3520 ± 725	3267–3773	–27	.900	222	6.30	1.0
	15–20	3438 ± 722	3186–3690	–109	.856	267	7.76	.76
	5–15	3623 ± 707	3376–3869	76	.963	135	3.74	.07
	10–15	3604 ± 731	3349–3859	57	.923	195	5.42	1.0

Abbreviations: CI, confidence interval; SE_E, standard error of estimate.

[a] Compared with criterion value.

*Significantly different from criterion value (P < .05).

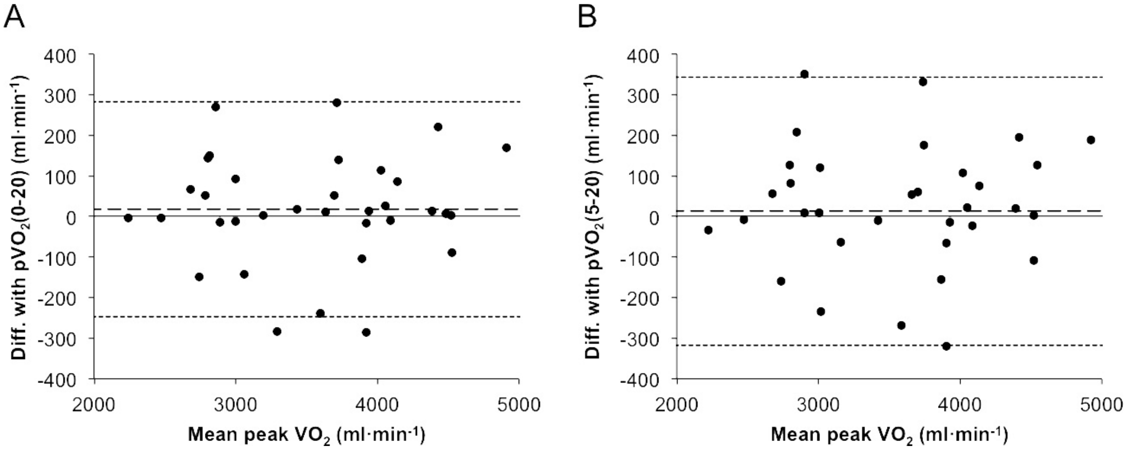

Figure 2 — Bland-Altman difference plots between oxygen uptake ($\dot{V}O_2$) at the end of exercise (criterion) and the 2 best estimates calculated by the model: (A) p$\dot{V}O_2$ (0–20) and (B) p$\dot{V}O_2$ (5–20). The equality (solid line), mean difference (long-dashed line), and 95% limits of agreement (short-dashed line) are depicted.

et al[14] is likely to underestimate true exercise $\dot{V}O_{2peak}$ by 3.3% on average (95% CI = 9.8% underestimation to 3.2% overestimation).

As previously explained, the model relies on the Fick principle (Eqs 1 and 2), and its basic assumption is that SV remains nearly constant during the first seconds of recovery (Eq 3). The validity of this assumption needs further discussion. After light to moderate exercise, it has been shown that SV does not fall as rapidly as HR does after exercise and remains above exercise levels[23] for as long as 3 to 5 minutes,[23,27,28] especially in the upright position.[28] Sustained high $\dot{Q}$ during the recovery phase was also demonstrated, explaining the on-/off-transient $\dot{V}O_2$ kinetics asymmetry (ie, slower off-transient time constant, also confirmed in 200-m maximal swimming[22]), appearing to be a result of both SV and HR being maintained to ensure a sufficiently high O_2 flow to the muscle during recovery at a time when the muscle $\dot{V}O_2$ remains high.[29] Therefore, the decrease in $\dot{Q}$ (and consequently $\dot{V}O_2$) would occur mainly by decreased postexercise HR. On the other hand, Sheldahl et al[30] suggested that the central redistribution of blood volume with head-out water-immersion cycling exercise at 40%, 60%, and 80% of $\dot{V}O_{2max}$, leading to an increase in SV without a proportional decrease in HR, evidences that $\dot{Q}$ is regulated at a higher level during upright exercise in water than during that on land. Although there is no available evidence that this response pattern takes place during maximal exercise, in line with these reports, some of our subjects showed a small rise in $\dot{V}O_2$ while HR remained constant immediately after the cessation of exercise, which can be loosely interpreted as a rise in SV. This rise could also be explained by the change in body position from horizontal to vertical; the lower part of the body is now deeply immersed and under a hydrostatic pressure gradient, which would translocate blood from the lower limbs and abdomen to the thoracic region, thus increasing venous return and SV compared with the horizontal position.[31] We suggest that this increase in SV is possibly the reason for the small overestimation of exercise $\dot{V}O_{2peak}$ when shorter time intervals were used, such as in calculating p$\dot{V}O_2$(5–15) and p$\dot{V}O_2$(10–15) (Table 1).

A second assumption of the model is that $C(a-\overline{v})O_2$ remains nearly constant during the first seconds of recovery. This assumption relies on the fact that a certain venous volume with constant O_2 saturation can be assumed to occur during the immediate recovery while arterial saturation is constant. Because of the distance between muscle and mouth, substantial changes in $C(a-\overline{v})O_2$ over the first seconds of recovery are not to be expected, as shown by Drescher et al.[17] As shown in Figure 1, p$\dot{V}O_2$ values do not decline over the first 20 seconds after the cessation of exercise, which is likely the time for the onset of changes in $C(a-\overline{v})O_2$ perceivable in the exhaled air. On the other hand, the high correlation and the low mean difference between p$\dot{V}O_2$ during exercise and p$\dot{V}O_2$(0–20) strengthen the validity of the physiological assumptions of the model. In the current findings, the $\dot{V}O_2$ off-kinetics are virtually parallel to HR off-kinetics during the first 20 seconds of recovery, suggesting that no substantial changes in $C(a-\overline{v})O_2$ and SV occurred within this time period. Therefore, it seems justified to use HR on- and off-kinetics as a proxy of $\dot{V}O_2$ dynamic response during early recovery within the limited scope of practical application of the model.

From another standpoint, the observation that p$\dot{V}O_2$(0–20) and p$\dot{V}O_2$(5–20) provided the smallest estimation bias of $\dot{V}O_{2peak}$ during exercise is in agreement with previous findings showing a time-variable delay in the $\dot{V}O_2$ recovery curve after maximal swimming.[15] Our results show that this was likely to be the reason for the ~20% overestimation of $\dot{V}O_{2peak}$ found by Lavoie et al[32] after a 400-m swim and the similar results reported by Costill et al,[14] who found a decline in $\dot{V}O_2$ during the first 20 seconds after the cessation of exercise causing an ~6% overestimation of $\dot{V}O_2$ after 4 to 7 minutes of tethered swimming. Differences in methods of assessment and instrumentation among these studies (eg, Douglas bags vs modern breath-by-breath oximeters) would certainly explain at least some of these discrepancies. Concerning the variability of the estimated parameters (Figure 2, Table 1), in which some predicted values deviate up to ~8% from measured values, we need to consider that the standard error of estimate (SE_E) for p$\dot{V}O_2$(0–20), the best predictor variable, was 3.82%, very similar to the SE_E for postexercise measured $\dot{V}O_2$ (4.15%). This suggests that the main reason for these larger deviations is measurement error, not inherent to the modeling procedure. Hyperventilation during the immediate recovery appears to be the most straightforward explanation.

Practical Applications

The proposed model minimizes the error in predicting $\dot{V}O_{2peak}$ from recovery measurements after a maximal swim, with the practical advantage of avoiding the use of respiratory equipment during swimming and, thus, allowing swimmers to use their normal breathing pattern and fully use high-speed swimming technique and the specifically trained muscle mass in pool conditions.

From a technical standpoint, 3 conditions are required to ensure the validity of the results: obtaining good beat-to-beat HR recordings, obtaining the first breath-by-breath $\dot{V}O_2$ values as fast as possible while avoiding missing breaths and hyperventilation (eg, as when swimmers are incorrectly advised to hold their breath during the final strokes), and monitoring HR and $\dot{V}O_2$ during a recovery period of at least 20 seconds to avoid overestimation or underestimation.

Further validation of the model would imply comparing direct $\dot{V}O_2$ measurements with model-predicted values on swimming bouts of different duration and intensity (eg, 100- to 400-m submaximal and maximal swims). In addition, more basic studies investigating directly measured $\dot{Q}$ kinetics after maximal swimming exercise would be required to confirm the physiological assumptions of the model.

Conclusion

We propose the new model, based on continuous beat-to-beat HR and postexercise breath-by-breath $\dot{V}O_2$ measurements during 20 seconds, as a valid and accurate procedure for estimating $\dot{V}O_{2peak}$ in competitive swimmers. This calculation method avoids the bias of $\dot{V}O_{2peak}$ estimations incurred by using the backward-extrapolation method and overcomes the constraints imposed by the use of respiratory equipment during swimming.

Acknowledgments

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Study II

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ARTICLE

Estimating peak oxygen uptake based on postexercise measurements in swimming

Diego Chaverri, Xavier Iglesias, Thorsten Schuller, Uwe Hoffmann, and Ferran A. Rodríguez

Abstract: To assess the validity of postexercise measurements in estimating peak oxygen uptake ($\dot{V}O_{2peak}$) in swimming, we compared oxygen uptake ($\dot{V}O_2$) measurements during supramaximal exercise with various commonly adopted methods, including a recently developed heart rate — $\dot{V}O_2$ modelling procedure. Thirty-one elite swimmers performed a 200-m maximal swim where $\dot{V}O_2$ was measured breath-by-breath using a portable gas analyzer connected to a respiratory snorkel, 1 min before, during, and 3 min postexercise. $\dot{V}O_{2peak}$(-20–0) was the average of the last 20 s of effort. The following postexercise measures were compared: (*i*) first 20-s average ($\dot{V}O_{2peak}$(0–20)); (*ii*) linear backward extrapolation (BE) of the first 20 s (BE(20)), 30 s, and 3 × 20-, 4 × 20-, and 3 or 4 × 20-s averages; (*iii*) semilogarithmic BE at 20 s (LOG(20)) and at the other same time intervals as in linear BE; and (*iv*) predicted $\dot{V}O_{2peak}$ using mathematical modelling ($p\dot{V}O_2$(0–20)]. Repeated-measures ANOVA and post-hoc Bonferroni tests compared $\dot{V}O_{2peak}$ (criterion) and each estimated value. Pearson's coefficient of determination (r^2) was used to assess correlation. Exercise $\dot{V}O_{2peak}$(-20–0) (mean ± SD 3531 ± 738 mL·min^{-1}) was not different ($p > 0.30$) from $p\dot{V}O_2$(0–20) (3571 ± 735 mL·min^{-1}), BE(20) (3617 ± 708 mL·min^{-1}), or LOG(20) (3627 ± 746 mL·min^{-1}). $p\dot{V}O_2$(0–20) was very strongly correlated with exercise $\dot{V}O_{2peak}$ ($r^2 = 0.962$; $p < 0.001$), and showed a low standard error of the estimate (146 mL·min^{-1}, 4.1%) and the lowest mean difference (40 mL·min^{-1}; 1.1%). We confirm that the new modelling procedure based on postexercise $\dot{V}O_2$ and heart rate measurements is a valid and accurate procedure for estimating $\dot{V}O_{2peak}$ in swimmers and avoids the estimation bias produced by other methods.

Key words: $\dot{V}O_{2max}$, oxygen kinetics, heart rate, backward extrapolation, modelling.

Résumé : Pour élucider la validité des mesures post-exercice pour l'estimation de la consommation pic d'oxygène ($\dot{V}O_{2pic}$) en natation, nous avons comparés diverses méthodes communément adoptées, y comprise une procédure de modélisation en base à la relation fréquence cardiaque — consommation d'oxygène ($\dot{V}O_2$). Trente et un nageurs d'élite ont nagé 200 m à intensité maximale. $\dot{V}O_2$ a été mesurée en utilisant un analyseur de gaz portable connecté à un tuba respiratoire, 1 min avant, pendant et pendant 3 min après de l'effort. $\dot{V}O_{2pic}$(-20–0) été la moyenne des 20 dernières secondes de l'effort. Les suivantes mesures post-exercice ont été comparées: (*i*) moyenne des premiers 20-s ($\dot{V}O_{2pic}$(0–20)); (*ii*) rétroextrapolation linéaire des 20 s (BE(20)) et des 30 s premières secondes, et moyennes des intervalles 2 × 20 s, 3 × 20 s et 3 ou 4 × 20 s; (*iii*) rétroextrapolation semilogarithmique à 20 s (LOG(20)) et aux mêmes intervalles de temps que celle linéaire; et (*iv*) modélisation mathématique sur 20 s ($p\dot{V}O_2$(0–20)). Chaque valeur a été comparée avec $\dot{V}O_{2pic}$ (critère) utilisant l'analyse de la variance pour mesures répétées. Le coefficient de Pearson (r^2) a été utilisé pour évaluer la corrélation. $\dot{V}O_{2pic}$(-20–0) (3531 ± 738 mL·min^{-1}) n'a pas été différente ($p > 0.3$) de $p\dot{V}O_2$(0–20) (3571 ± 735 mL·min^{-1}), BE(20) (3617 ± 708 mL·min^{-1}), ou LOG(20) (3627 ± 746 mL·min^{-1}). $p\dot{V}O_2$(0–20) a été fortement corrélée avec $\dot{V}O_{2pic}$(-20–0) ($r^2 = 0962$; $p < 0,001$) et a montré une faible erreur type d'estimation (4,1 %) et la plus basse différence moyenne (1,1 %). On confirme que le nouveau modèle est une procédure valide et précise pour estimer la $\dot{V}O_{2pic}$ chez les nageurs, tout en évitant les biais d'estimation produits par d'autres méthodes.

Mots-clés : $\dot{V}O_{2max}$, cinétique de l'oxygène, rythme cardiaque, cinétique de la fréquence cardiaque, rétroextrapolation, modélisation.

Introduction

In swimming, measuring oxygen uptake ($\dot{V}O_2$) is a complex and unwieldy procedure. Recently, portable gas analyzers connected to face masks (e.g., Rodríguez 1995, 2000) or swimming snorkels (e.g., Keskinen et al. 2003; Rodríguez et al. 2008; Baldari et al. 2013) have facilitated this task, providing the investigators with an acceptable level of practicality and accuracy. Nevertheless, measuring $\dot{V}O_2$ using a swimming snorkel might involve changes in stroke kinematics (Keskinen et al. 2001; Barbosa et al. 2010), swimming technique (e.g., reducing body rolling), and normal breathing pattern, and make impossible diving starts and flip turns (Kjendlie et al. 2003; Kapus et al. 2006).

To solve this problem, Montpetit et al. proposed to use postexercise measurements and the backward extrapolation (BE) method — first described by Di Prampero et al. (1976) and later validated by Léger et al. (1980) for treadmill running — for swimming, and validated this technique against Douglas bag measures in a multistage free-swimming and treadmill running (Montpetit et al. 1981). In their original study, directly measured exercise maximal oxygen uptake ($\dot{V}O_{2max}$) was compared with values estimated through the linear BE of the $\dot{V}O_2$ recovery curve at time zero using semilogarithmic single-exponential least-squares regression on the first three or four 20-s bag content values. No significant differences were found between $\dot{V}O_{2max}$ measured and

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estimated by BE and the standard error of the estimate (SEE) was 3.7%. From then, BE is often used for estimating $\dot{V}O_2$ during swimming (Léger et al. 1980; Montpetit et al. 1981; Ribeiro et al. 1990; Zamparo et al. 2008; Zamparo and Swaine 2012), but an error can derive from a delay at the onset of the $\dot{V}O_2$ recovery curve after supramaximal exercise, which has been consistently described as lasting 5–35 s for maximal exercise to up to 1 min (Di Prampero et al. 1973). In fact, Lavoie et al. suggested that this time-variable delay was responsible for the ~20% overestimation of peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$) when using BE after an unimpeded 400-m maximal swim and, to circumvent this problem, they were the first to propose a single 20-s postexercise gas collection during recovery as a good and practical indicator of $\dot{V}O_{2peak}$ in swimming (Lavoie et al. 1983). Two years later, Costill et al. (1985) further validated this simplified method in tethered breaststroke swimming and found a high correlation (r^2 = 0.96) between exercise and 20-s recovery $\dot{V}O_{2peak}$, although observing a decline in $\dot{V}O_2$ (~6%) during the first 20 s of recovery. Later, using continuous breath-by-breath (BxB) postexercise measurements, Rodríguez corroborated the existence of a time delay after an all-out 400-m swimming exercise at about 3–10 s at the onset of the $\dot{V}O_2$ recovery phase (Rodríguez 1999). Sousa et al. modelled the $\dot{V}O_2$ kinetics response during and after a square-wave maximal swim at 100% of $\dot{V}O_{2peak}$ using a double-exponential function and reported an average time delay of 11 s (Sousa et al. 2015). A very recent study reported a time delay of 14.2 ± 4.7 s during an all-out 100-m swim, which was longer in female (15.1 s) compared with male swimmers (13.8 s), (Rodríguez et al. 2016).

Recently, a new evaluation procedure based on heart rate (HR) and postexercise $\dot{V}O_2$ measurements for estimating $\dot{V}O_{2peak}$ at the end of a swimming exercise has been implemented (Chaverri et al. 2016). This method showed very highly correlated (r^2 = 0.963) and practically identical values compared with $\dot{V}O_2$ measured using a swimming snorkel during supramaximal swimming (mean Δ = 17 mL·min⁻¹), hence solving the problem of overestimation. The study also showed an underestimation when $\dot{V}O_{2peak}$ was calculated using a single postexercise 20-s measurement (3.3% ± 1%).

Therefore, to elucidate the validity of postexercise $\dot{V}O_2$ measurements in estimating $\dot{V}O_{2peak}$ in swimming, we compared direct $\dot{V}O_2$ BxB measurements during supramaximal exercise with various procedures for estimating exercise $\dot{V}O_2$ from measurements during the recovery period, including a recently developed HR-$\dot{V}O_2$ modelling procedure based on the Fick's principle.

Materials and methods

Participants

T1 Thirty-one elite swimmers, all members of national and Olympic teams, including 18 females and 13 males (Table 1), gave their written informed consent to participate in the study, which had received approval from the Ethics Committee for Clinical Sport Research of Catalonia and follow the legal requirements and the Declaration of Helsinki (Harriss and Atkinson 2013).

Testing

After an ~30-min standard warm-up, the subjects rested outside the water while the respiratory equipment was set up and calibrated for the measurements. Afterwards the swimmers performed an all-out 200-m front crawl swim using the swimming snorkel (Table 1). During the test, an assistant carried the respiratory equipment walking beside the swimmer at the edge of the pool. After exercise the swimmers remained in an upright position for 3 min and were immersed in the water to the midsternum. All tests were conducted at a 50-m indoor pool (altitude 190 m above sea level; water temperature 26–27 °C; air temperature 27–28 °C).

Table 1. Subject characteristics and 200-m all-out swimming test performance.

	Females (n = 18)	Males (n = 13)	All (n = 31)
Age (y)	20.3±3.8	22.2±2.9	21.1±3.5
Height (cm)	172.9±5.4	187.9±6.0	179.2±9.4
Body mass (kg)	63.3±5.4	82.1±7.2	71.2±11.2
FPS	856±75	840±44	849±63
Time 200 m (s)	144.3±7.1	135.8±8.1	140.7±8.5
Mean velocity 200 m (m·s⁻¹)	1.389±0.066	1.478±0.085	1.426±0.086

Note: Values are means ± SD. FPS, FINA (Fédération Internationale de Natation) Point Scores.

Data collection and processing

$\dot{V}O_2$ was measured using a telemetric portable gas analyzer (K4 b², Cosmed, Italy) connected to the swimmer by a previously validated low hydrodynamic resistance respiratory snorkel and valve system (Keskinen et al. 2003; Rodríguez et al. 2008). Pulmonary gas exchange values during the maximal swim were measured 1 min before, during, and 3 min after exercise. HR was continuously measured using beat-by-beat monitors (CardioSwim, Freelap, Switzerland). Measured $\dot{V}O_2$ and HR data were time-aligned to the start of the measurements, 1-s interpolated, and plotted against time.

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

Two $\dot{V}O_{2peak}$ values during exercise were identified: (*i*) $\dot{V}O_{2peak}$ (-20–0): averaged values measured within the last 20 s of exercise (t_{-20}–t_0) — these values were taken as the criterion value for all comparisons; and (*ii*) $\dot{V}O_{2peak}$ nonlinear regression ($\dot{V}O_{2peak}$(NLR)): pulmonary $\dot{V}O_2$ values during swimming were measured BxB, time-aligned to the start of exercise, and plotted against time. No smoothing procedures were applied to avoid distortion of the underlying signal at the transient phase. $\dot{V}O_2$ data were fitted using a nonlinear least-square regression technique (Matlab R2010b, Mathworks, USA). For the analysis of $\dot{V}O_2$ kinetics, the first 2 phases of the generally adopted 3-phase model were identified, since the exercise duration and intensity constrained the appearance of the slow component (Scheuermann and Barstow 2003). Phase I (cardiodynamic component) was determined as the time from the onset of exercise to a point of sharper increase in $\dot{V}O_2$, and its duration was computed as a time delay for the primary component (TD$_p$). Phase II (principal component) parameters were estimated using a monoexponential model according to the following equation:

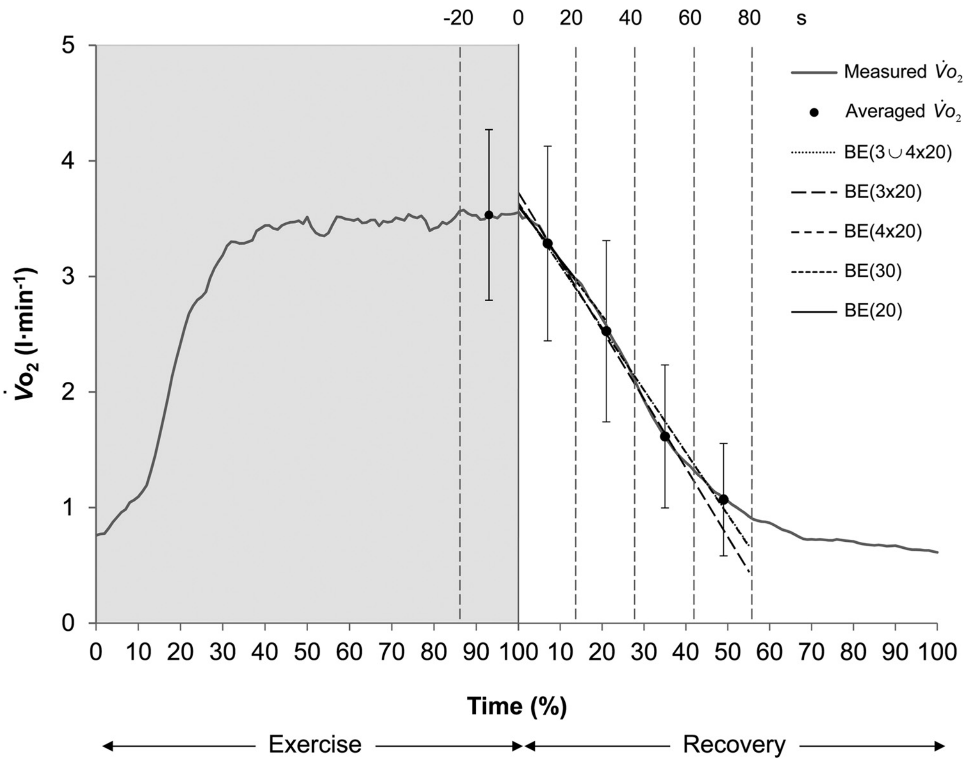
$$(1)\qquad \dot{V}O_2(t) = A_0 + A_p \cdot [1 - e^{-(t-\mathrm{TD_p})/\tau_p}]$$

where t (s) is the time from the onset of exercise; A_0 is the baseline amplitude; A_p is the amplitude of the principal component; TD$_p$ (s) is the time delay of the first exponential term and equals the duration of phase I (cardiodynamic component); and τ_p is the time constant of the principal component. The total amplitude (A_{tot}) was calculated as $A_{tot} = A_0 + A_p$. The reliability of $\dot{V}O_{2peak}$ measurements was characterized by a typical error of 3.1% (95% confidence interval (95% CI): 1.1%–5.1%; n = 9).

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

Three different techniques were used to estimate $\dot{V}O_{2peak}$ from HR and/or $\dot{V}O_2$ kinetics during recovery period: (*i*) lineal BE, (*ii*) semi-logarithmic BE, and (*iii*) modelling procedures. First, 6 different procedures were used to estimate $\dot{V}O_{2peak}$ using the linear BE technique: (*i*) $\dot{V}O_{2peak}$(20–0); (*ii*) BE(20): estimated value calculated by BE to time zero (t_0) of the first 20-s values of the $\dot{V}O_2$ recovery curve; (*iii*) BE(30): estimated $\dot{V}O_{2peak}$ by BE to t_0 of the first 30-s values of the $\dot{V}O_2$ recovery curve; (*iv*) BE(3x20): BE value calculated from the first three 20-s average values of the $\dot{V}O_2$ recovery curve;

Fig. 1. Schematic diagram of $\dot{V}O_2$ (grey line, average 1-s values for the entire group of swimmers) measured during exercise (shadowed area) and recovery at a 200-m all-out swim. Discontinuous grey 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 (both linear and semilogarithmic) projected on the t_0 of recovery, were used to estimate $\dot{V}O_{2peak}$ using the different BE procedures. Only linear BE regressions are shown here for clarity. See text for definitions and details.



(*v*) BE(4x20): BE value calculated from the first four 20-s average values of the $\dot{V}O_2$ recovery curve; and (*vi*) BE(3∪4x20): estimated value calculated by BE to t_0 of the best linear regression fit (3x20-s or 4x20-s) of the $\dot{V}O_2$ recovery curve.

Second, the same estimations were performed using the semilogarithmic procedure (LOG), i.e., plotting the logarithms of the $\dot{V}O_2$ measured values as a function of recovery time and backward extrapolating to t_0 as in the original paper of Léger et al. (1980). Using analogous notation, 5 different calculations were computed to estimate $\dot{V}O_{2peak}$: (*i*) LOG(20), (*ii*) LOG(30), (*iii*) LOG(3x20), (*iv*) LOG(4x20), and (*v*) LOG(3∪4x20).

Third, $\dot{V}O_{2peak}$ was estimated using a modelling technique: $p\dot{V}O_2(0–20)$: 20-s averaged values of the predicted $\dot{V}O_2$ based on the HR and $\dot{V}O_2$ kinetics during the recovery period following the procedure previously described by Chaverri et al. (2016). Based on the 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:

$$p\dot{V}O_2(t) = \dot{V}O_2(t) \cdot HR_{\text{end-exercise}}/HR(t) \tag{2}$$

with $p\dot{V}O_2$ (t) as the predicted (modelled) postexercise $\dot{V}O_2$ at time t; $\dot{V}O_2$ (t) as the postexercise 1-s interpolated $\dot{V}O_2$ at time t; HR (t) as the postexercise 1-s interpolated HR value at time t; and $HR_{\text{end-exercise}}$ as the highest HR value of the last 10 s of exercise (single peaks higher than 5 beats/min than the last 10-s HR average excluded).

Statistical analysis

Descriptive data are expressed as means and standard deviations (±SD), and mean differences (mean Δ). The normality of the distributions and homogeneity of variance were checked by the Shapiro–Wilks and Levene tests, respectively. A 1-way analysis of variance (ANOVA) with repeated measures (RM-ANOVA) and post hoc Bonferroni test when appropriate were used for multiple comparisons between exercise (criterion value) and each of the postexercise measured and estimated values. Sphericity was checked by Mauchly's sphericity test. The Pearson's coefficient of determination (r^2) was used to assess correlation between variables and the goodness-of-fit of regression models, which was further assessed by using a cross-validation (CV) procedure. Data were split into 2 half subsamples (CV_1, CV_2) and their regression parameters were calculated and then used to estimate a set of predicted values for the other subsample. r^2 for the observed and predicted data for each subsample (r^2_{CV1}, r^2_{CV2}) were then computed. The SEE, expressed as absolute values and percentage of the mean, and the limits of the 95% CI were calculated. Differences between measured and estimated $\dot{V}O_{2peak}$ and the level of agreement (mean Δ ± 1.96SD) were analyzed graphically using Bland–Altman difference plots (Bland and Altman 1986). Under- and overestimation are defined as the difference between estimated and criterion mean values expressed in percentage of the criterion's mean. The level of significance was set at $P < 0.05$. Statistical analyses were conducted using SPSS for Windows (version 18; SPSS Inc., PASW Statistics for Windows, Chicago, Ill., USA).

Results

Figure 1 shows $\dot{V}O_2$ measured during the all-out 200-m swim and during recovery, and $\dot{V}O_{2peak}$ estimated during recovery using the various linear BE techniques. The same time intervals were used for the logarithmic BE methods. Irrespectively of the calculation procedure, all BE techniques overestimated exercise $\dot{V}O_{2peak}$ as a consequence of the time-variable delay at the immediate recovery (9.1 ± 4.8 s; range = 2–22 s; 95% CI = 7.3–10.9 s).

Table 2. Peak $\dot{V}O_2$ measured during exercise and $\dot{V}O_{2peak}$ values measured and estimated by different procedures during recovery.

Technique	Procedure	Peak $\dot{V}O_2$ (mL·min⁻¹)	95% CI (mL·min⁻¹)		Mean diff. (mL·min⁻¹)	Mean diff. (%)	r^2	CV r^2 r^2_{CV1}	CV r^2 r^2_{CV2}	SEE (mL·min⁻¹)	SEE (%)	Significance* (p)
Exercise (criterion)	$\dot{V}O_{2peak}$(-20–0)	3531±738	3260	3802	—	—	—	—	—	—	—	—
	$\dot{V}O_{2peak}$(NLR)	3479±727	3213	3746	−52	−1.5	0.977	0.966	0.991	113.5	3.2	1.000
Lineal BE	$\dot{V}O_{2peak}$(0–20)	3378±698	3122	3635	−153	−4.5	0.969	0.969	0.974	132	3.7	<0.001*
	BE(20)	3617±708	3357	3876	86	2.4	0.956	0.959	0.962	216	5.6	0.393
	BE(30)	3658±719	3394	3921	127	3.5	0.967	0.968	0.972	136	3.6	0.001*
	BE(3x20)	3828±762	3549	4107	297	7.8	0.950	0.954	0.953	169	4.8	<0.001*
	BE(4x20)	3763±780	3477	4049	232	6.2	0.924	0.947	0.928	207	5.9	<0.001*
	BE(3∪4x20)	3823±746	3549	4096	292	7.6	0.946	0.957	0.944	175	5.0	<0.001*
Semilogarithmic BE	LOG(20)	3627±711	3366	3888	96	2.6	0.949	0.950	0.959	169	4.8	0.301
	LOG(30)	3686±722	3421	3951	155	4.2	0.958	0.956	0.970	154	4.3	<0.001*
	LOG(3x20)	4175±768	3894	4457	644	15.4	0.863	0.874	0.864	278	7.9	<0.001*
	LOG(4x20)	4400±884	4076	4724	869	19.7	0.688	0.852	0.616	420	11.9	<0.001*
	LOG(3∪4x20)	4302±819	4002	4602	771	17.9	0.772	0.885	0.694	358	10.1	<0.001*
Modelling	$p\dot{V}O_{2peak}$(0–20)	3571±735	3301	3841	40	1.1	0.962	0.955	0.977	146	4.1	1.000

Note: See text for defintions.

T2 As shown in Table 2, $\dot{V}O_{2peak}$(NLR) and $\dot{V}O_{2peak}$(-20–0) values were very strongly correlated (r^2 = 0.977; p < 0.001), although $\dot{V}O_{2peak}$(NLR) gave nonsignificant, slightly lower values as compared with the criterion (mean Δ = –1.5%; p = 1.000). All estimated $\dot{V}O_{2peak}$ values differed from the criterion, except BE(20) (p = 0.393), LOG(20) (p = 0.301), and $p\dot{V}O_{2peak}$(0–20) (p = 1.000). $p\dot{V}O_{2peak}$(0–20) predicted values were almost identical (mean Δ = 1.1%) and very strongly correlated with criterion measurements (r^2 = 0.962; p < 0.001; SEE = 4.1%). The r^2 calculated by cross-validation confirms the robustness of the estimations and the validity of the comparisons.

F2 The regression and different plots in Fig. 2 show a strong correlation (r^2 = 0.962; p < 0.001) and a good level of agreement between criterion-exercise $\dot{V}O_{2peak}$ and model-predicted $p\dot{V}O_{2peak}$(0–20) values.

F3 Figure 3 shows the regression and difference plots for the estimated $\dot{V}O_2$ values using linear BE techniques (see Table 1 for statistics). All BE methods except $\dot{V}O_{2peak}$(0–20) (Fig. 3A) overestimated exercise $\dot{V}O_{2peak}$. Larger mean differences and 95% limits of agreement were common to BE(3x20), BE(4x20), and BE(3∪4x20) (Figs. 3D–3F), whereas BE(20) and BE(30) showed the lowest mean difference and best level of agreement with criterion values (Fig. 3A–3C). From these parameters, only BE(20) was not significantly different from the criterion (p = 0.393).

F4 Figure 4 shows the regression and difference plots for the estimated $\dot{V}O_2$ values using semilogarithmic BE techniques. Again, all techniques overestimated $\dot{V}O_{2peak}$ measured during exercise. Only LOG(20)and LOG(30) (Fig. 3A, 3B) showed a satisfactory level of agreement and high correlations with criterion values (r^2 = 0.949 and r^2 = 0.958, respectively).

Discussion

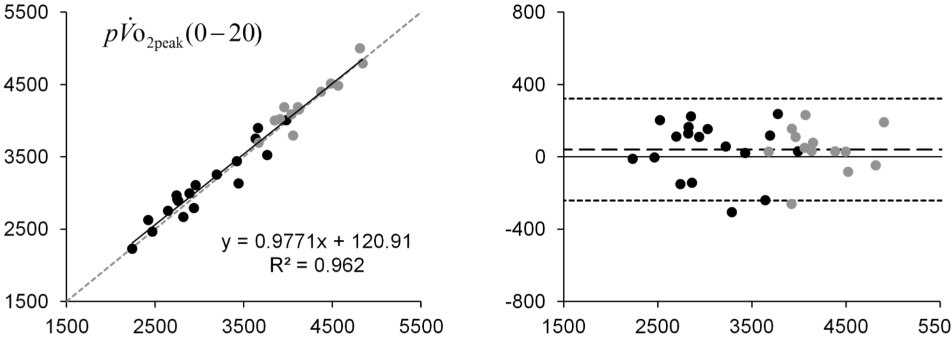
To assess the validity of postexercise measurements for estimating $\dot{V}O_{2peak}$ in swimming, we compared measured $\dot{V}O_{2peak}$ during a 200-m all-out swim using a respiratory snorkel and $\dot{V}O_{2peak}$ estimated from postexercise values during the same test according to various commonly adopted procedures. The main findings were (*i*) postexercise $\dot{V}O_2$ measurements estimated exercise $\dot{V}O_{2peak}$ in elite competitive swimmers with good accuracy; (*ii*) the overestimation of $\dot{V}O_{2peak}$ exhibited by the BE methods can be explained by a slower decay of the $\dot{V}O_2$ curve at the onset of the recovery period (~10 s on average); (*iii*) the present results confirm our previous observations that the new modelling method based on HR kinetics and postexercise $\dot{V}O_2$ measurements is the most valid and accurate procedure for estimating $\dot{V}O_{2peak}$ after a maximal swim.

Two procedures were used to quantify $\dot{V}O_{2peak}$ during swimming: $\dot{V}O_{2peak}$(-20–0) was the 20-s average at the end of the swim and $\dot{V}O_{2peak}$(NLR) was obtained by nonlinear double-exponential regression. Confirming previous results (Rodríguez et al. 2015), both values did not differ and were nearly perfectly correlated (r^2 = 0.977), albeit $\dot{V}O_{2peak}$(-20–0) showed slightly greater values (mean Δ = 1.5%). We chose $\dot{V}O_{2peak}$(-20–0) as the reference criterion for all comparisons for a number of reasons (Chaverri et al. 2016): (*i*) to ensure that only last swimming lap data were used; (*ii*) to minimize inter-breath fluctuations; (*iii*) to prevent overestimation of $\dot{V}O_{2peak}$ values frequently obtained with shorter time intervals (de Jesus et al. 2014); (*iv*) to maintain exercise and recovery temporal equality according to the on/off symmetry in the $\dot{V}O_2$ kinetic response (Sousa et al. 2011*a*); and (*v*) previous work showed that 20-s average values produced the same $\dot{V}O_{2peak}$ as the total amplitude obtained by nonlinear fitting of the $\dot{V}O_2$ on-kinetics during 200-m maximal swims (Rodríguez et al. 2015).

Concerning the different approaches used to estimate $\dot{V}O_{2peak}$ using postexercise $\dot{V}O_2$ measurements, they have in common the advantage of allowing the athlete to swim completely unimpeded (i.e., without mouthpiece, snorkel, and tubing) and to attain maximal exertion without any modification of the swimmer's technique and hydrodynamics (i.e., breathing pattern, diving starts and turns and subsequent underwater gliding phase, and body position and drag). This is particularly relevant in high-velocity swimming, such as in time trials to determine $\dot{V}O_{2peak}$. It has been shown that maximal velocity attained in 100-m (Barbosa et al. 2010) or 400-m all-out tests (Lavoie et al. 1983) is faster when swimming unimpeded (~13%–16% and ~5%–6%, respectively), the disparity being explained by the longer distance and the subsequent cumulative effect of altered conditions along the swim. During multistage continuous tests, mean differences of ~10% in maximal velocity (Keskinen et al. 2001) and in maximal velocity at $\dot{V}O_{2max}$ (Montpetit et al. 1981) were also found.

Notwithstanding, the key issue is whether estimated values from postexercise measurements are in good agreement with those directly measured during exercise. The most straightforward method is collecting expired air during the first 20 s of the immediate recovery (Lavoie et al. 1983; Costill et al. 1985; Ribeiro et al. 1990). In the present study, $\dot{V}O_{2peak}$(0–20) underestimated exercise values by 4.5% (Table 2, Fig. 3A), which is in agreement with the original findings of Costill et al., who reported ~6% lower values using a 20-s single measure as compared with directly measured $\dot{V}O_{2peak}$ after 5–7 min of tethered swimming at maximal intensity (Costill et al. 1985). A greater underestimation (~7.6%) was found by Lavoie et al. after an all-out unimpeded 400-m swim (Lavoie et al. 1983). Here, contrary to these earlier studies, $\dot{V}O_2$ was directly measured BxB, thus confirming that the bias is caused mainly by a quick decrease of the $\dot{V}O_2$ curve at the onset of the recovery as previously documented in the literature (Di Prampero et al. 1973; Roberts and Morton 1978; Rodríguez 1999; Sousa

Fig. 2. Relationship between exercise $\dot{V}O_{2peak}$ values — i.e., $\dot{V}O_{2peak}$(-20–0), *x* axis — and $\dot{V}O_{2peak}$ estimated using the HR-$\dot{V}O_2$ modelling procedure — i.e., $p\dot{V}O_{2peak}$(0–20), *y* axis. Males (grey dots) and females (black dots) are shown separately. In the left panel, regression line (solid back) and equality line (dashed grey) are shown. Linear regression equation and coefficient of determination are shown in the left panel. In the right panel, the *x* axis represents mean $\dot{V}O_2$ (mL·min^{-1}) and the *y* axis shows the differences with exercise $\dot{V}O_2$. Lines are equality (solid), mean difference (long-dashed), and ±95% limits of agreement (short-dashed). All data are expressed in mL O_2·min^{-1}. See text for definitions and details.



et al. 2011*a*). In contrast, the other 2 methods used in the present study and based in short collection periods yet using the BE technique — i.e., linear and semilogarithmic regression from 20- and 30-s continuous measurements, respectively — overestimated $\dot{V}O_{2peak}$ by 2.4% to 4.2%, though only BE(20)and LOG(20) offered values that were not different from the criterion method (Table 1; Figs. 3B, 4A). Thus, BE of continuously measured values during 20 s, whether in absolute values or transformed into their logarithms, appears to provide better $\dot{V}O_{2peak}$ estimates than 20-s average of BxB postexercise measurements or the equivalent 20-s bag sample classical technique.

Backward extrapolation methods

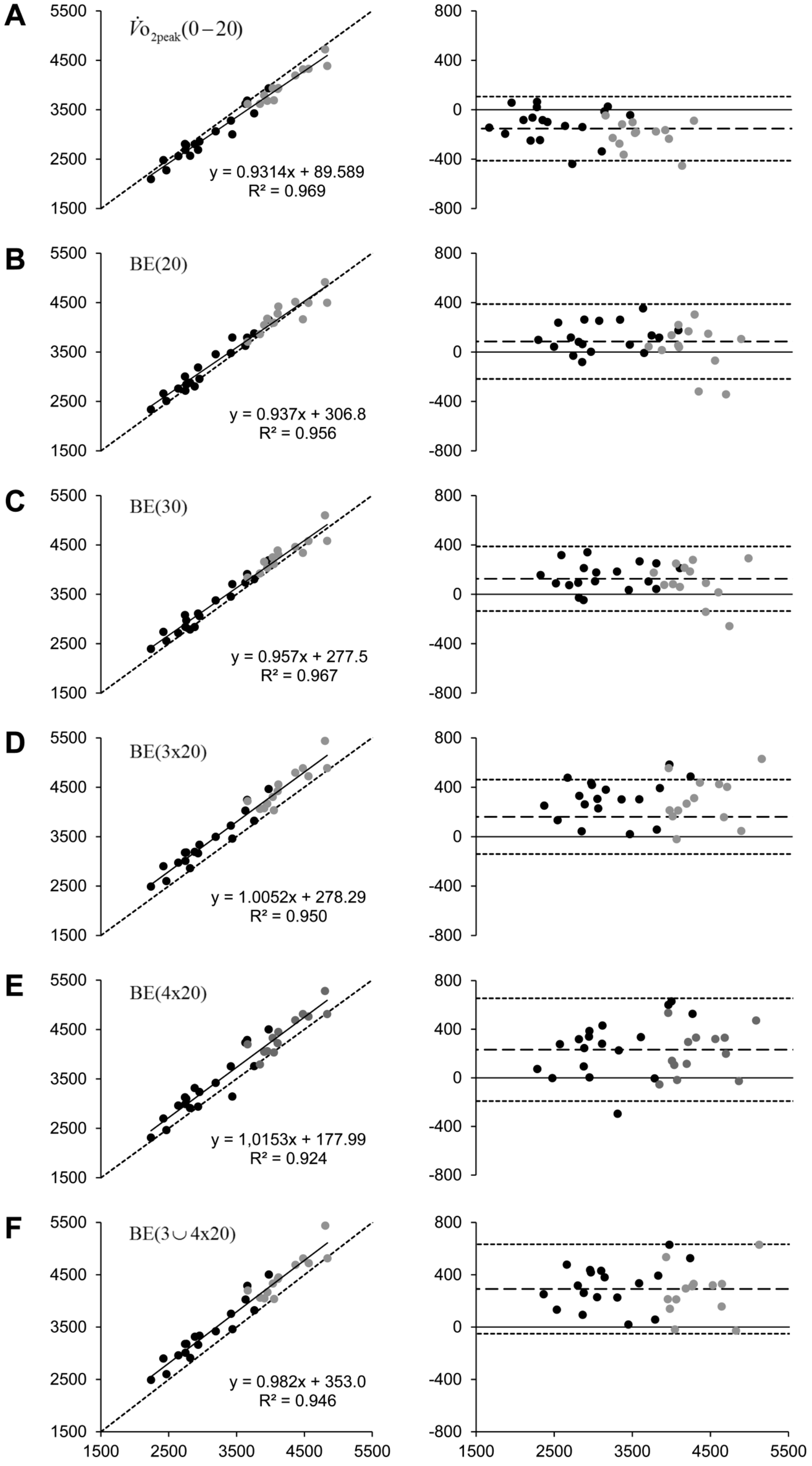
As to the classical BE methods (i.e., extrapolation to t_0 of the recovery of average values obtained during 60 to 80 s), they all provided values that differed ($p < 0.001$) and systematically overestimated (6.2% to 19.7%) exercise measurements despite showing relatively good correlation with criterion values (r^2 = 0.688 to 0.950) (Table 2, Figs. 1 and 2). Lavoie et al. reported a similar overestimation (~20%) when using the semilogarithmic BE method (linear regression of three or four 20-s bag samples) after a maximal 400-m swim, and attributed this substantial discrepancy to a time delay in the $\dot{V}O_2$ recovery curve (Lavoie et al. 1983). This phenomenon was first reported by di Prampero et al. who observed that contrary to steady state aerobic exercise, $\dot{V}O_2$ remains practically at exercise levels for about 12–35 s after cessation of supramaximal leg-cycling exercise of very short duration (11–51 s) (Di Prampero et al. 1973). An indirect proof is offered by the work of Costill et al. who observed a close correlation between post exercise 20-s $\dot{V}O_2$ values and $\dot{V}O_{2peak}$ (r^2 = 0.96), with a relatively small mean difference (~6%), but decreasing correlation during subsequent recovery periods (20–40 s, r^2 = 0.94; 40–60 s, r^2 = 0.52; 60–80 s, r^2 = 0.59) (Costill et al. 1985). Later, using BxB equipment, Rodríguez confirmed the existence of a time delay after an all-out 400-m swimming exercise of about 3–10 s at the onset of the $\dot{V}O_2$ recovery curve in competitive swimmers (Rodríguez 1997, 1999). Using the same procedure and discarding the individual time delay, no significant differences were found between $\dot{V}O_{2max}$ determined with continuous postexercise, single 30-s measurements after a maximal 400-m swimming test compared with $\dot{V}O_{2max}$ measured during maximal incremental cycle ergometer and treadmill tests (Rodríguez 2000). In a study in which the $\dot{V}O_2$ on- and off-kinetics response was measured after a square-wave swimming exercise at the severe intensity domain (i.e., 100% of $\dot{V}O_{2max}$) sustained during 3.3 ± 0.4 min and modelled using a double-exponential regression function, the time delay of the fast component was 10.9 ± 6.4 s (Sousa et al. 2015). Finally, a recent study reported a time delay of 14.2 ± 4.7 s during an all-out 100-m swim, being longer in female (15.1 s) compared with male swimmers (13.8 s) (Rodríguez et al. 2016). The present results corroborate that the overestimation observed when BE of 20 to 80 s values are used to predict $\dot{V}O_{2peak}$ during supramaximal exercise is caused by the time delay during the immediate recovery being that: (*i*) as evidenced in Fig. 1, there is slower decay of the $\dot{V}O_2$ curve at the onset of the recovery period; (*ii*) visual inspection of each $\dot{V}O_2$ curve confirmed a time-variable delay in most swimmers (9.1 ± 4.8 s); and (*iii*) there were no differences from the criterion when $\dot{V}O_{2peak}$ was calculated using 20-s sampling averages (i.e., BE(20) and LOG(20)), whereas differences existed in all BE methods when longer sampling times were used. Moreover, a previous validation study using the same mathematical modelling procedure showed that sampling times up to 20 s offered the smallest estimation bias of $\dot{V}O_{2peak}$ after maximal 200-m tests (Chaverri et al. 2016).

Mathematical modelling procedure

To avoid the problem of under- and overestimation in BE methods, our group developed a mathematical modelling procedure based on $\dot{V}O_2$ off-kinetics and HR on- and off-kinetics, which gave satisfactory results in predicting end-exercise $\dot{V}O_{2peak}$ following an all-out 200-m swim (Chaverri et al. 2016). In that study, the best end-exercise $\dot{V}O_{2peak}$ estimates were provided by $p\dot{V}O_{2peak}$(0–20), i.e., values modelled during the first 20 s of the recovery (r^2 = 0.963; mean Δ = 0.5%; SEE = 3.8%). Using the same HR-$\dot{V}O_2$ modelling procedure, the present study corroborates its validity and accuracy, as almost identical results were obtained (r^2 = 0.962; mean Δ = 1.1%; SEE = 4.1%) (Table 2, Fig. 2).

Altogether, the present study provides evidence that most methods for determining $\dot{V}O_{2peak}$ from postexercise measurements following a supramaximal swimming effort are most likely to under- or overestimate exercise values as a consequence of the kinetic characteristics of the $\dot{V}O_2$ off-response. As previously discussed, the main reason for the underestimation of the single postexercise 20-s measurement (~5%–8%) is the rapid decay of $\dot{V}O_2$ during the immediate recovery (i.e., fast component), characterized by a time constant of ~60–70 s on average (Sousa et al. 2011*a*, 2015). On the other hand, the main cause for the overestimation incurred by all BE techniques (~6%–20%) is the time-variable delay of the same fast component, which has been quantified in ~11 ± 6 s for all-out swimming exercise (Sousa et al. 2015) and found to be 9.1 ± 4.8 s in this study. Differently, the HR-$\dot{V}O_2$ modelling procedure is based on the Fick's principle and calculates a predicted $\dot{V}O_2$ at a given time of recovery using the HR as a proxy for changes in cardiac output, and the oxygen pulse as a proxy for the arterio-venous O_2 difference (Chaverri et al. 2016). This procedure has shown to provide valid and accurate estimations of exercise $\dot{V}O_{2peak}$ without significant bias (mean Δ = 0.5%–1.1%; p = 1.0).

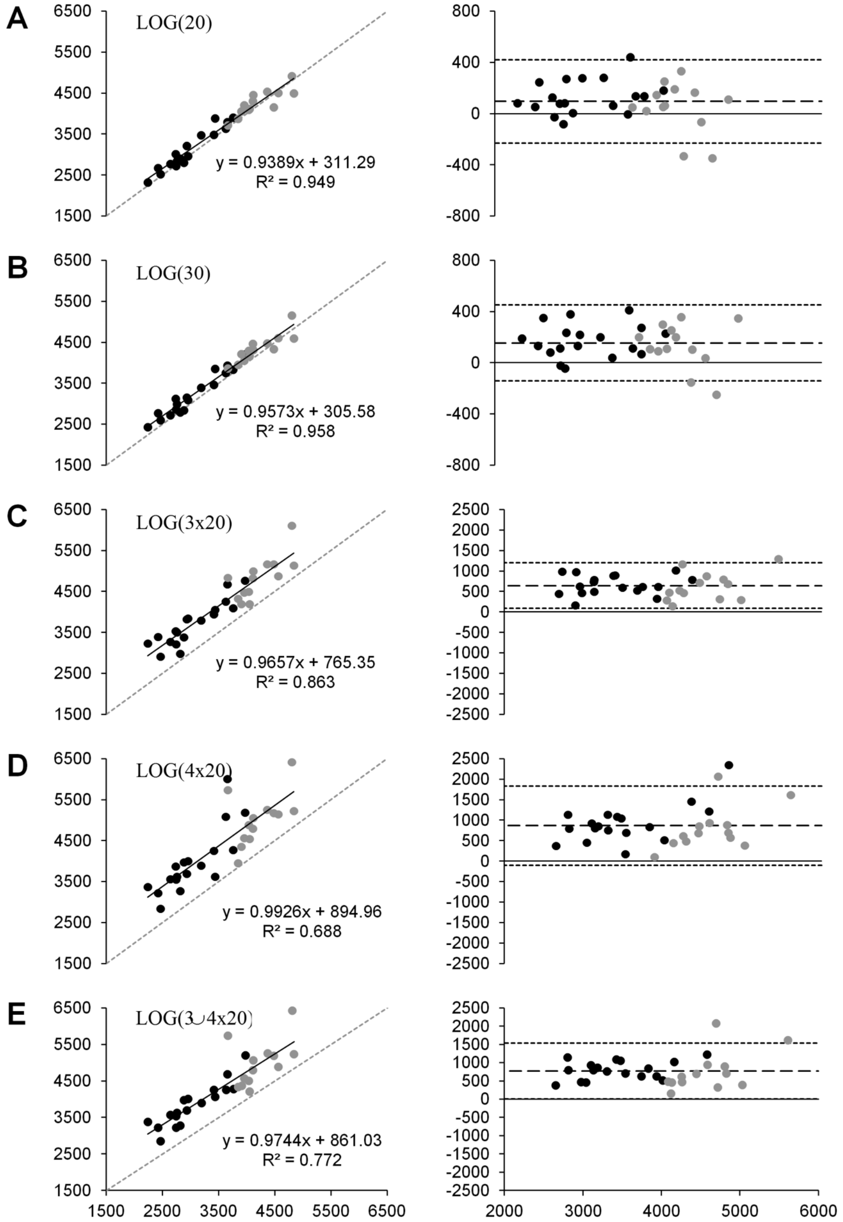
Fig. 3. Relationship between exercise $\dot{V}O_{2peak}$ values — i.e., $\dot{V}O_{2peak}$(-20–0), *x* axis) — and $\dot{V}O_{2peak}$ estimated using different linear BE methods: (A) $\dot{V}O_{2peak}$(0–20), (B) BE(20), (C) BE(30), (D) BE(2x20), (E) BE(4x20), and (F) BE(3∪4x20). Regression and difference Bland–Altman plots are presented as in Fig. 2. See text for definitions and details.



Study limitations

Despite the fact that 200-m maximal swims have been widely adopted in studies with competitive swimmers (Reis et al. 2010; Sousa et al. 2010, 2011*a*; 2011*b*; Figueiredo et al. 2011; Fernandes et al. 2012; Chaverri et al. 2015; Rodríguez et al. 2015) — namely because of the very strong activation of both the aerobic and anaerobic energy metabolism (Rodríguez and Mader 2011) and its average duration (~2–2.5 min on average), which is sufficient to elicit $\dot{V}O_{2max}$. in most cases (Morgan et al. 1989; Rossiter et al. 2006) — it needs to be acknowledged that the present study focused on this particular distance and on the extreme intensity domain. Although we do not anticipate relevant outcome modifi-

Fig. 4. Relationship between exercise $\dot{V}O_{2peak}$ values — i.e., $\dot{V}O_{2peak}$(-20–0), *x* axis — and $\dot{V}O_{2peak}$ estimated using different linear semilogarithmic BE methods: (A) LOG(20), (B) LOG(30), (C) LOG(3x20), (D) LOG(4x20), and (E) LOG(3∪4x20). Regression and difference Bland–Altman plots are presented as in Figs. 2 and 3. See text for definitions and details.



cations from changes in these 2 factors, further studies focusing on other distances or durations and submaximal intensities are warranted. Likewise, since this study involved elite swimmers, it seems of interest to investigate swimmers of lower competitive level and younger age.

Practical applications

The use of BxB respiratory equipment at the poolside has improved the feasibility and validity of gas exchange assessment in swimming. Using specifically designed snorkels, despite the advantage of allowing continuous measurements during exercise and recovery, still faces some limitations such as precluding diving starts and flip turns, changing stroke kinematics, modifying the breathing pattern, and causing a sometimes unbearable discomfort. Using postexercise $\dot{V}O_2$ measurements allows the swimmers to exercise completely unimpeded and to exploit their maximal potential with any undue limitation caused by the equipment whatsoever. Nevertheless, as the present results show, the BE technique results in substantial overestimation of $\dot{V}O_{2peak}$(~6%–20%). Using regression techniques on BxB data are likely to reduce measurement error (2%–3%; $p = 0.3–0.4$), hence providing a greater level of accuracy in $\dot{V}O_{2peak}$ measurements. Considering that the swimmers typically vary their individual performance in the range of about ~3% across the competitive season (Pyne et al. 2001; Anderson et al. 2006), the large measurement error reported by BE techniques (linear and semilogarithmic) compromise their ability to monitor progress in elite swimmers. Instead, using the proposed model minimizes the error in predicting $\dot{V}O_{2peak}$ (1.1%) and provides a valid and accurate method to measure progress in high-level athletes. Moreover, these HR measurements, can be taken without any interference to the normal swimming pattern and can provide scientific and coaches additional information, e.g., training load (García-Ramos et al. 2015). Important to note that some technical conditions are required to ensure the validity of the results (Chaverri et al. 2015): (*i*) obtaining quality beat-to-beat HR recordings, (*ii*) obtaining the first BxB $\dot{V}O_2$ values as fast as possible while avoiding missing breaths and hyperventilation, and (*iii*) monitoring HR and $\dot{V}O_2$ during the recovery period for at least 20 s.

Conclusions

Measurement accuracy is key to postexercise gas exchange assessment in pool conditions for estimating exercise $\dot{V}O_{2\text{peak}}$. From the present study, in which measured $\dot{V}O_{2\text{peak}}$ during 200-m maximal swimming exercise was compared with $\dot{V}O_{2\text{peak}}$ estimations from postexercise measurements according to various commonly adopted procedures in elite swimmers, we may derive the following conclusions: (*i*) some (but not all) postexercise $\dot{V}O_2$ estimation techniques allowed to predict exercise $\dot{V}O_{2\text{peak}}$ with good accuracy; (*ii*) the large overestimation exhibited by the classical BE methods (~6%–20%) can be explained by a time-variable delay of the fast component of the $\dot{V}O_2$ off-kinetic response (~10 s on average); (*iii*) BE methods using linear and semilogarithmic regression of shorter measurement periods (0–20 s) provided more accurate results, but still overestimate $\dot{V}O_{2\text{peak}}$ by ~2%–3%, respectively; (*iv*) the widely adopted 20-s average method underestimates $\dot{V}O_{2\text{peak}}$ by ~5% because of the rapid decrease of $\dot{V}O_2$ during the immediate recovery (fast component); and (*v*) the HR-$\dot{V}O_2$ modelling technique, based on continuous beat-to-beat HR and postexercise BxB $\dot{V}O_2$ measurements during 20 s, is confirmed as a valid and accurate procedure for estimating $\dot{V}O_{2\text{peak}}$ in competitive swimmers without significant bias (0.5%–1.1%). Therefore, the HR-modelling technique appears to be the method of choice for assessing cardiorespiratory and metabolic fitness in competitive swimmers when postexercise measurements are chosen to avoid the burden of respiratory equipment during swimming exercise.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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Study III

Validity of postexercise measurements to estimate oxygen uptake in 200-m and 400-m maximal swimming tests

Journal:	*International Journal of Sports Medicine*
Manuscript ID	Draft
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Validity of postexercise measurements to estimate oxygen uptake in 200-m and 400-m maximal swimming tests

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. Twenty-five elite swimmers performed a 200-m maximal swim where $\dot{V}o_2$ was measured using a swimming snorkel connected to a gas analyser. The criterion variable was $\dot{V}o_{2peak}$ 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, 3x20-s, 4x20-s, and 3x20-s or 4x20-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 two 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.

Key words

Maximal oxygen uptake, modelling, oxygen kinetics, heart rate kinetics, testing, backward extrapolation

Introduction

Breath-by-breath (bxb) oxygen uptake ($\dot{V}o_2$) 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 analysers [2,22,36,43]. However, the use of such equipment changes the swimmer's technique and hydrodynamics, resulting in lower swimming speeds [3,21,24]. Estimating $\dot{V}o_2$ from postexercise measurements taken after swimming seems to be a plausible alternative provided that the error of estimation is sufficiently low. Di Prampero et al. 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 maximal peak $\dot{V}o_2$ ($\dot{V}o_{2\text{peak}}$) during exercise with BE estimates from recovery measures [25].

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., who found that although swimmers attained a 10% increase in swimming speed during a maximal multistage swim when the BE method was used, the measured and estimated $\dot{V}o_{2\text{peak}}$ values were well correlated and the SE_E was low (3.7%). Since then, this technique has often been used for estimating $\dot{V}o_2$ during swimming [18,24,48,49]. 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 [26]. In this sense, previous studies conducted with the Douglas bag technique reported a time delay of 12 to 35 s at the onset of the $\dot{V}\text{o}_2$ recovery curve after supramaximal exercise [9,20,30]. Recent studies using bxb measurements confirmed the existence of a delay of ~3 to 14 s [5,31,37,44]. This delay at the onset of the $\dot{V}\text{o}_2$ recovery curve is likely the cause of the overestimation (20%) described by Lavoie et al. after a supramaximal 400-m swim when $\dot{V}\text{o}_{2\text{peak}}$ was estimated by BE using postexercise Douglas bag measurements [24]. In a recent study published using bxb equipment, we found that linear and semilogarithmic BE at different time intervals systematically overestimated the $\dot{V}\text{o}_{2\text{peak}}$ measured during a 200-m supramaximal swim by 3.5% to 17.9% [5].

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 $\dot{V}\text{o}_{2\text{peak}}$ in swimming [24]. Two years later, the simplified procedure was adopted by Costill et al., and they reported a high correlation with the $\dot{V}\text{o}_{2\text{peak}}$ measured during 7 min of tethered breaststroke swimming, though they also observed a small decline in $\dot{V}\text{o}_2$ 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% [7] and -4.5% [5] of the measured values when $\dot{V}\text{o}_{2\text{peak}}$ 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 $\dot{V}\text{o}_2$ measurements for estimating $\dot{V}\text{o}_{2\text{peak}}$ at the end of an all-out swimming test [5,7]. The estimated values calculated on the first 20 s upon recovery (t_0-t_{20}) showed almost identical results (mean $\Delta = 0.5\%$) and a low SE_E (3.8%) compared with the exercise $\dot{V}\text{o}_{2\text{peak}}$ 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}) [7]. Hence, this new modelling procedure has been shown to be the most accurate procedure for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ and overcomes the bias incurred by other methods. However, previous research is limited to 200-m supramaximal swimming and involved continuous $\dot{V}\mathrm{o}_2$ 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.

It is well known that competitive 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]. Therefore, $\dot{V}\mathrm{o}_{2\,\mathrm{max}}$ is considered to be an important performance factor as an expression of maximal aerobic power. Traditionally, incremental tests have been mostly used to test $\dot{V}\mathrm{o}_{2\mathrm{max}}$ in swimmers (see [43] for a review). Few studies have assessed the measured $\dot{V}\mathrm{o}_{2\mathrm{max}}$ in elite swimmers in pool conditions within the range of race speeds and times. $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was shown to be very closely related to performance at 100 m (r^2= 0.62) and 400 m (r^2= 0.56) distances among competitive swimmers [35], and the amplitude and time delay of the principal component of $\dot{V}\mathrm{o}_2$ combined were found to explain 46% of the variance of the 100-m performance [38].

However, the question of whether $\dot{V}\mathrm{o}_{2\,\mathrm{max}}$ can be attained during a maximal incremental and/or all-out swimming test is controversial, but this is key to the physiological evaluation of swimmers. In his pioneering work, Holmér compared the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ measured using the Douglas bag method in the swimming flume, treadmill running and cycling and found a higher $\dot{V}o_{2\mathrm{peak}}$ in running than in swimming [16]. Some years later, using bxb technology during recovery, Rodríguez did not find differences in

$\dot{V}o_{2\text{peak}}$ between a 400-m maximal swim and incremental laboratory cycling and running tests [33]. The later results were attributed to very fast $\dot{V}o_2$ on-kinetics in competitive swimmers [35,37,41,45]. This issue needs to be clarified at least in relation to what can be called the "swim-specific" $\dot{V}o_{2\text{max}}$ determination, i.e., the maximal $\dot{V}o_2$ attainable during supramaximal swimming.

Therefore, we aimed: 1) to assess the validity of postexercise $\dot{V}o_2$ measurements in estimating $\dot{V}o_{2\text{peak}}$ by comparing $\dot{V}o_2$ measured directly using a swimming snorkel connected to a bxb gas analyser 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 $\dot{V}o_{2\text{max}}$ among competitive swimmers.

Methods

Participants

In series A, eight elite female swimmers were recruited as subjects via their national and/or Olympic teams. In series B, seventeen elite swimmers, also members of their national and/or Olympic teams, consisting of 12 females and 5 males (table 1), volunteered to participate. The FINA Point Scoring (FPS) system was used to quantify their competitive level, and a point score (range 0-1100) was ascribed to each swimmer according to her/his best time in her/his main event, scaled up or down from 1000 points based on the fastest global yearly performance in each event (table 1).

All swimmers were fully informed about the study and provided written informed consent to participate, which adhered to the requirements of the Declaration of Helsinki and current ethical standards [14], as well as the IJSM Ethical Standards [15]; this study received approval from the Governmental Ethics Committee [Blinded for review].

– Table 1 –

Testing

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

– Figure 1 –

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.

In series A, during a second session taking place at least 24 h after the first, the subjects performed a 200-m all-out time trial test with the front crawl stroke (200TT). A competition start was used, and the swimmers, who swam alone, were instructed to achieve the best time possible. Time was recorded to the nearest 0.01 s by three 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, $\dot{V}\mathrm{o}_2$ was continuously measured bxb using a telemetric portable gas analyser (K4 b^2, Cosmed, Italy) connected to the swimmer by a low hydrodynamic resistance respiratory snorkel and valve system, which has been previously validated [22,36]. Pulmonary gas exchange during the maximal swim was measured 1 min before, during, and 3 min after exercise. HR was continuously measured using beat-by-beat monitors (CardioSwim, Freelap, Switzerland). $\dot{V}\mathrm{o}_2$ 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 unimpeded (figure 1). $\dot{V}\mathrm{o}_2$ was collected using an oronasal Hans-Rudolph 7400 mask 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. Expiratory gases were collected using a Hans-Rudolph 7400 silicone oronasal mask (Hans Rudolph Inc., Shawnee, Kansas, USA), which was firmly applied immediately after the swim with care to avoid leakage and to minimise the time before the first respiratory data were obtained. The swimmers were instructed about the proper technique before the swims. HR was continuously monitored as in the previous tests.

Measured $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ during exercise

$\dot{V}\mathrm{o}_{2\mathrm{peak}}$ during exercise was taken as the averaged values measured within the last 20 s of exercise (t_{-20}–t_0), referred to as $\dot{V}\mathrm{o}_{2\mathrm{peak}}(-20-0)$, and taken as the criterion value for all comparisons. Two previous studies showed that $\dot{V}\mathrm{o}_{2\mathrm{peak}}(-20-0)$ did not differ from $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ calculated by fitting the 1-s interpolated bxb data to a nonlinear least-square regression using a biphasic $\dot{V}\mathrm{o}_2$ kinetics model [7,34]. The reliability of $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ measurements using this procedure are characterized by a typical error of 3.1% (95% confidence interval, 95% CI: 1.1–5.1%; $n = 9$) [34].

Estimated $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ from postexercise measurements

As in a previous study [5], the following three techniques were used to estimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ from HR and/or $\dot{V}\mathrm{o}_2$ kinetics during recovery: 1) linear BE, 2) semilogarithmic BE, and 3) HR/$\dot{V}\mathrm{o}_2$ modelling procedures. Figure 2 shows the averaged $\dot{V}\mathrm{o}_2$ 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.

– Figure 2 –

Figures 1 and 2 summarize which variables were analysed in each experimental series, but for the sake of order, we will define their groups here. First, the following six procedures were used in the BE technique: 1) $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$ – 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 $\dot{V}\mathrm{o}_2$ recovery curve; 3) BE(30) – estimated $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ by BE to the t_0 of the first 30-s values of the $\dot{V}\mathrm{o}_2$ recovery curve; 4) BE(3x20) – BE value calculated from the first three 20-s average values of the $\dot{V}\mathrm{o}_2$ recovery curve; 5) BE(4x20) – BE value calculated from the first four 20-s average values of the $\dot{V}\mathrm{o}_2$ recovery curve; and 6) BE(3∪4x20) – estimated value calculated by BE to the t_0 of the best regression fit (3x20 s or 4x20 s) of the $\dot{V}\mathrm{o}_2$ recovery curve.

Second, the same estimations were performed using a semilogarithmic procedure (LOG), i.e., the logarithms of the measured $\dot{V}\mathrm{o}_2$ 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. [25]. Using analogous notation, the following five calculations were computed to estimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$: 1) LOG(20); 2) LOG(30); 3) LOG(3x20); 4) LOG(4x20); and 5) LOG(3∪4x20).

Third, $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was estimated using a HR/$\dot{V}\mathrm{o}_2$ modelling technique, where $p\dot{V}\mathrm{o}_2(0-20)$ is the 20-s averaged values of the predicted $\dot{V}\mathrm{o}_2$ based on the HR and $\dot{V}\mathrm{o}_2$ kinetics according to the procedure described elsewhere [7]. In short, based on Fick's principle, the model calculates a predicted $\dot{V}\mathrm{o}_2$ 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:

$$p\dot{V}\mathrm{o}_2(t) = \dot{V}\mathrm{o}_2(t) \cdot \mathrm{HR}_{\mathrm{end-exercise}} \,/\, \mathrm{HR}(t) \qquad \text{(Eq. 1)}$$

where $p\dot{V}\mathrm{o}_2(t)$ is the predicted (modelled) postexercise $\dot{V}\mathrm{o}_2$ at time *t*; $\dot{V}\mathrm{o}_2(t)$ is the postexercise 1-s interpolated $\dot{V}\mathrm{o}_2$ at time *t*; HR(*t*) is the postexercise 1-s interpolated HR value at time *t*; and $\mathrm{HR}_{\mathrm{end\text{-}exercise}}$ is the 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).

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 assessed 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 each postexercise estimating procedure. In series B, two-way RM-ANOVA and post-hoc Bonferroni tests, when appropriate, were used for multiple comparisons between $\dot{V}\mathrm{o}_2$ during exercise (criterion) and for estimated values, comparisons between the two tests, and the test-by-procedure interaction. Pearson's coefficient of determination (r^2) was used to assess correlation between variables. 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 [17]. 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ and the level of agreement (mean Δ ± 1.96 SD) were analysed graphically using Bland-Altman difference plots [4]. 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

In 200TT, a time gap from t_0 to the first valid $\dot{V}\mathrm{o}_2$ measurement of 3.4 ± 1.9 s, and a fast component TD (light grey area in figure 2) of 7.6 ± 4.4 s were observed. Table 2 compares the criterion of $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ measured during exercise (200SS) with that estimated using different procedures from postexercise measurements after an unimpeded 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., $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ and $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$, which showed almost perfect correlation with the criterion values ($r^2 >$ 0.84) and the lowest mean differences (mean $\Delta < 1.6\%$) and had a low estimation bias (SE_E = 7%). Linear BE methods overestimated the criterion values by 7.6% to 13.3%, on average, whereas $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$ underestimated the measured values by 3.4%.

– Table 2 –

The regression and Bland-Altman plots in figure 3 also show an almost identical perfect correlation and a good level of agreement between the two modelling procedures, with $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ offering a slightly better predictive capacity (see table 2 for statistics).

– Figure 3 –

Series B

In 200SS, a fast component TD (light grey area in figure 2) of 9.5 ± 4.8 s was noted. In 400TT, there was a time gap from t_0 to the first valid $\dot{V}\mathrm{o}_2$ measurement of 2.8 ± 2.4 s, and a fast component TD of 6.7 ± 4.2 s. Table 3 compares the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$, which underestimated the criterion $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$ at 400TT.

– Table 3 –

As shown in table 4, the semilogarithmic BE procedures did not differ from the criterion, with the exceptions of LOG(20) in both 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 to 18.1%) in both 200TT and 400TT.

– Table 4 –

No differences were noted between the criterion $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ values and those estimated using the HR/$\dot{V}\mathrm{o}_2$ modelling procedure (table 5), and there was slightly lower bias and better predictive capacity shown by $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$, 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). Figure 4 shows the corresponding regression and Bland-Altman difference plots for both variables in 200TT and 400TT.

– Table 5 –

– Figure 4 –

Table 6 shows the linear regression equations between the criterion and $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ 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 figures 3, 4 and 5 for regression statistics.

-- Table 6–

Discussion

To assess the validity of postexercise measurements to estimate the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ after a supramaximal swim, we compared the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ 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 unimpeded (200TT and 400TT). The main findings were as follows: 1) $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ 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 $\dot{V}\mathrm{o}_2$ measurement; 2) the modelling procedure based on HR and recovery $\dot{V}\mathrm{o}_2$ kinetics appears to be the most valid and accurate procedure for estimating $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ after a maximal swim; and 3) both 200-m and 400-m all-out swims are valid tests for assessing swim-specific $\dot{V}\mathrm{o}_{2\mathrm{max}}$ when swimmers are fully unimpeded and when the measurements are combined with HR and postexercise $\dot{V}\mathrm{o}_2$ measurements.

It has been shown that the speed attained in all-out 100-m [3] or 400-m tests [24] is faster when the swimmer swims unimpeded (~13-16% and ~5-6%, respectively). During multistage continuous tests, mean differences of ~10% in maximal speed [21] and in maximal speed at $\dot{V}\mathrm{o}_{2\mathrm{max}}$ [26] were found. In fact, the use of swimming snorkels might alter stroke kinematics [3,21], swimming technique (e.g., by reducing body rolling), and breathing patterns, and they make it impossible to perform diving starts and flip turns [19,23], which result in lower swimming speeds. Therefore, estimating the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ using postexercise measurements, which enables the swimmers to perform completely unimpeded (i.e., without mouthpiece, snorkel, and tubing), is a clear advantage for pool testing and research, provided that $\dot{V}\mathrm{o}_2$ can be estimated with sufficient accuracy.

Series A

In these experiments, $\dot{V}\mathrm{o}_2$ 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) (figure 1). Thus, in the 200TT test, there was a time-variable gap between the end of the exercise and the start of $\dot{V}\mathrm{o}_2$ bxb measurements (3.4 ± 1.9 s). The present results confirm our previous observations in which $\dot{V}\mathrm{o}_2$ was measured uninterruptedly [5,7], showing that the new HR/$\dot{V}\mathrm{o}_2$ modelling technique most accurately predicts $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ regardless of whether the calculation is made using the first 0 to 20 s or the 5 to 20 s after the end of the exercise (mean $\Delta < 1.6\%$) (1.1%, op. cit.) (table 2, figure 3). Conversely, the linear BE methods largely overestimated the criterion values by 7.6% to 13.3% (7.6% and 2.4%, op. cit.). The classical single 20-s measurement technique, instead, underestimated the criterion values by 3.4%; lower values were reported by Lavoie et al. in relation to a 400-m supramaximal swim (-7.7%) [24] and by Costill et al. in relation to a 7-min tethered breaststroke swim (-6%) [8], 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ estimations. Additionally, it supports the validity and accuracy of the new HR/$\dot{V}\mathrm{o}_2$ modelling technique.

Series B

Although 200-m maximum swims have been widely adopted in studies that test competitive swimmers [5,7,11,12,29,34,41,42], for reasons discussed below, other authors have used longer distances or longer durations (i.e., 400 m, 5-7 min) for assessing $\dot{V}\mathrm{o}_{2\mathrm{max}}$ in swimmers [8,24,32,33]. Therefore, in the second series of experiments, $\dot{V}\mathrm{o}_2$ was first measured during exercise and recovery at 200SS, and then, $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was compared with postexercise measurements obtained after a separate 400TT test (figure 1), in which a time gap also existed between the end of the exercise and the first $\dot{V}\mathrm{o}_2$ bxb measurements (2.8 ± 2.4 s).

As in series A, the HR/$\dot{V}\mathrm{o}_2$ modelling technique was the best predictor of $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ (table 5, figure 4), notably when the calculation was made using the first 5 to 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%) [5]. 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 two previous studies [5,7].

The BE techniques (i.e., extrapolation to t_0 of the recovery of average values obtained during 60 to 80 s) all yielded a larger bias both for the 200TT (mean Δ range = 4.2% to 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% to 18.1%, and 11.0% to 16.8% for 200TT and 400TT tests, respectively), which makes them useless for the estimation of $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ during swimming. These results closely replicate those of our previous study, which used an identical methodology, during a 200SS test in which $\dot{V}\mathrm{o}_2$ was measured uninterruptedly [5]; 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∪4x20) (i.e., linear regression of three or four 20-s bag samples) [24]. 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, $\dot{V}\mathrm{o}_2$ 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 [46]. In swimming, Costill et al. provided indirect proof by observing the close correlation between postexercise 20-s average $\dot{V}\mathrm{o}_2$ values and the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ ($r^2 = 0.96$), with relatively small mean differences (~6%), though the correlation decreased during subsequent recovery periods [8]. Using bxb measurements, we observed a T D after an all-out 100-m swim of ~14 s [37] and between 3 and 10 s after a 400-m maximum test [31]. Similar results (~11 s) were obtained by Sousa et al. during a square-wave maximal swim at 100% of $\dot{V}o_{2\mathrm{max}}$ using a double-exponential function [44] and by Chaverri et al. during a 200-m supramaximal swim (9.1 ± 4.8 s) [5]. 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ during supramaximal exercise is caused by the time-variant delay during the immediate recovery, such that: 1) as evidenced in figure 1 (also observed in [5]), there is a slower rate of decrease of the $\dot{V}\mathrm{o}_2$ curve at the onset of the recovery period; 2) the analysis of the accurately timed individual $\dot{V}\mathrm{o}_2$ curves allowed to quantify this TD in most swimmers; 3) underestimation of the criterion values was observed when $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ was calculated using the 20-s sampling averages (i.e., $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$), 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 $\dot{V}\mathrm{o}_2$ recovery curve in a linear function. As opposed to the BE methods, the HR-$\dot{V}\mathrm{o}_2$ modelling technique is based on Fick's principle and predicts $\dot{V}\mathrm{o}_2$ during recovery using the HR as a proxy for changes in cardiac output and the oxygen pulse as a proxy for the arterio-venous O_2 difference (see [7] for discussion). This procedure, notably when excluding the first 5 s of recovery, i.e., $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$, has been shown to provide the most accurate estimations of exercise $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ without significant bias; in this study, the mean Δ range = 1.1% for 200TT [5], 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ at single-distance supramaximal tests can be considered to be swimmers' true $\dot{V}\mathrm{o}_{2\mathrm{max}}$. As opposed to multistage incremental tests, e.g., 3-7x200 m (see [43] for a review), single-distance all-out tests enable the swimmers to attain race speeds provided they can swim fully unimpeded. To date, 200-m swims have been widely adopted in studies that test competitive swimmers [5,7,11,12,29,34,41,42] because of the intense activation of both the aerobic and anaerobic energy metabolism [39] and because the duration (~2-2.5 min on average) is sufficient to elicit $\dot{V}\mathrm{o}_{2\mathrm{max}}$ in most cases [27,40]. It is possible that shorter or longer distances could limit its attainment, despite the extremely fast $\dot{V}\mathrm{o}_2$ kinetics of swimmers, as discussed below. In this study, no differences were noted between $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ at 200TT and 400TT tests (3194 ± 706 vs. 3245 ± 651; $p = 0.62$), suggesting that both distances yield the same $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ in competitive swimmers.

Concerning the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ vs. $\dot{V}\mathrm{o}_{2\mathrm{max}}$ controversy, which is not restricted to swimming, Holmér compared the $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ measured using the Douglas bag method in a swimming flume with that obtained during laboratory running and cycling and reported a higher $\dot{V}o_{2\mathrm{peak}}$ 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%) [16]. However, Rodríguez observed no differences in $\dot{V}o_{2\text{peak}}$ 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 $\dot{V}o_{2\text{max}}$ determination [33]. Moreover, the same author reported that a group of swimmers who reached their $\dot{V}o_{2\text{max}}$ during an incremental 5x400-m test attained ~95% of $\dot{V}o_{2\text{max}}$ during an all-out 100-m swim [31]. In line with previous results, Chaverri et al. did not find differences in the $\dot{V}o_{2\text{peak}}$ reached at three swimming distances (50, 100 or 200, and 400 m) swum at maximal speed [6]. 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 [37], 11 s in 200 m [34,41,45], and 17 s (when corrected using the same biexponential model) in 400-m all-out swims [35]. 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 [37]. 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. Although we do not anticipate large discrepancies because this study involved only elite swimmers, it is of interest to investigate swimmers at lower competitive levels and especially at younger ages.

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 $\dot{V}\mathrm{o}_2$ 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ (~4-20%). Considering that swimmers typically vary their individual performance in the range of ~3% across the competitive season [1,28], the large measurement error exhibited by the BE techniques (linear and semilogarithmic) largely compromises their ability to monitor progress in elite swimmers. The proposed modelling procedure, however, minimizes the error in predicting $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ (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 unimpeded 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$. From the present study, we may conclude the following: 1) $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ 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 $\dot{V}\mathrm{o}_2$ measurement; 2) BE methods using linear and semilogarithmic regressions overestimate $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ by ~4–14% due to a time-variable delay of the fast component of the $\dot{V}\mathrm{o}_2$ off-kinetic response (~10 s on average), which does not affect the

HR/$\dot{V}o_2$ modelling technique; 3) the widely 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 $\dot{V}o_{2max}$. 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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[Blinded for review]

Conflict of interests

[Blinded for review]

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FIGURES

Figure 1. Schematic of the experimental procedures for series A and B. In the timeline blocks, grey shadowed areas denote continuous $\dot{V}\mathrm{o}_2$ and heart rate measurements, whereas white areas denote heart rate measurements only ($\dot{V}\mathrm{o}_2$ was measured during the recovery period only). See the text for details.

Figure 2. Schematic diagram of $\dot{V}\mathrm{o}_2$ (continuous line, 1-s averaged values for the entire group of swimmers) measured during exercise (black line, dark shadowed area) and recovery (red 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 $\dot{V}\mathrm{o}_2$ measurements. Discontinuous vertical lines illustrate time limits (s) in which $\dot{V}\mathrm{o}_2$ 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ using the various BE procedures. See the text for definitions and details.

Figure 3. Series A: Comparison between $\dot{V}\mathrm{o}_2$ measured during exercise (200SS)—criterion $\dot{V}\mathrm{o}_{2\mathrm{peak}}(-20-0)$ in the x-axis—and estimated from postexercise measurements after 200TT using the HR/ $\dot{V}\mathrm{o}_2$ modelling procedure: (A) $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$ and (B) $p\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$. 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 $\dot{V}\mathrm{o}_{2\mathrm{peak}}$ values; lines represent equality (solid), mean difference (long-dashed), and ±95% limits of agreement (short-dashed). All data are expressed in $\mathrm{mlO_2 \cdot min^{-1}}$.

Figure 4. Series B. Comparison between the $\dot{V}\mathrm{o}_2$ measured during exercise (200SS)—criterion $\dot{V}\mathrm{o}_{2\mathrm{peak}}(-20-0)$ in the x-axis—and estimated from postexercise measurements using the HR/$\dot{V}\mathrm{o}_2$ 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 figure 3.

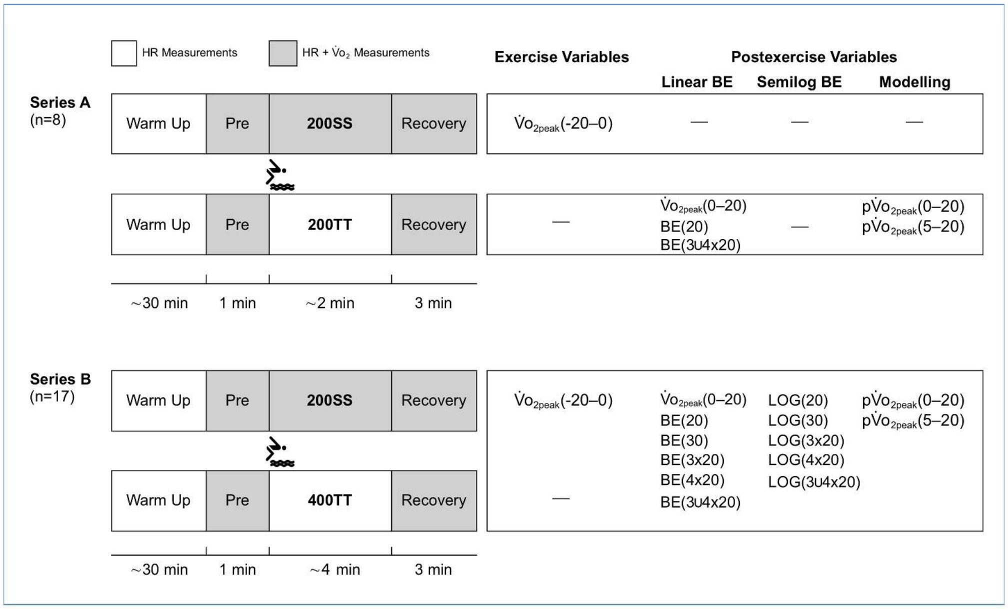

Figure 1. Schematic of the experimental procedures for series A and B. In the timeline blocks, grey shadowed areas denote continuous VO_2 and heart rate measurements, whereas white areas denote heart rate measurements only (VO_2 was measured during the recovery period only). See the text for details.
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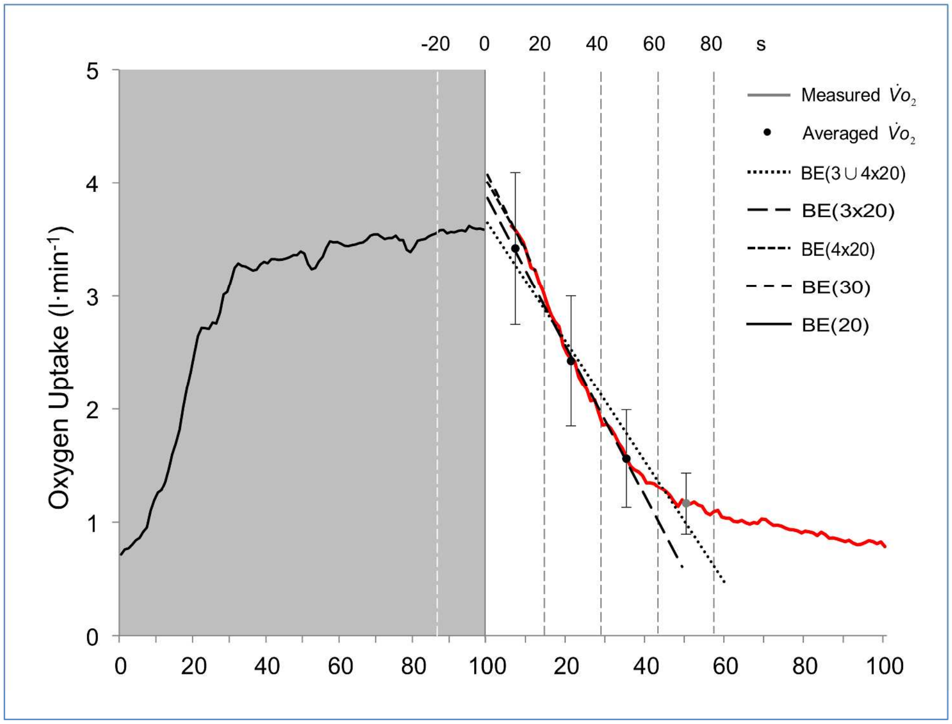

Figure 2. Schematic diagram of VO_2 (continuous line, 1-s averaged values for the entire group of swimmers) measured during exercise (black line, dark shadowed area) and recovery (red line) during a 200-m all-out swim. The double x-axis represents the percentage of exercise and recovery total time. The lighter grey area represents the time delay of postexercise VO_2 measurements. Discontinuous vertical lines illustrate time limits (s) in which VO_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 VO_{2peak} using the various BE procedures. See the text for definitions and details.
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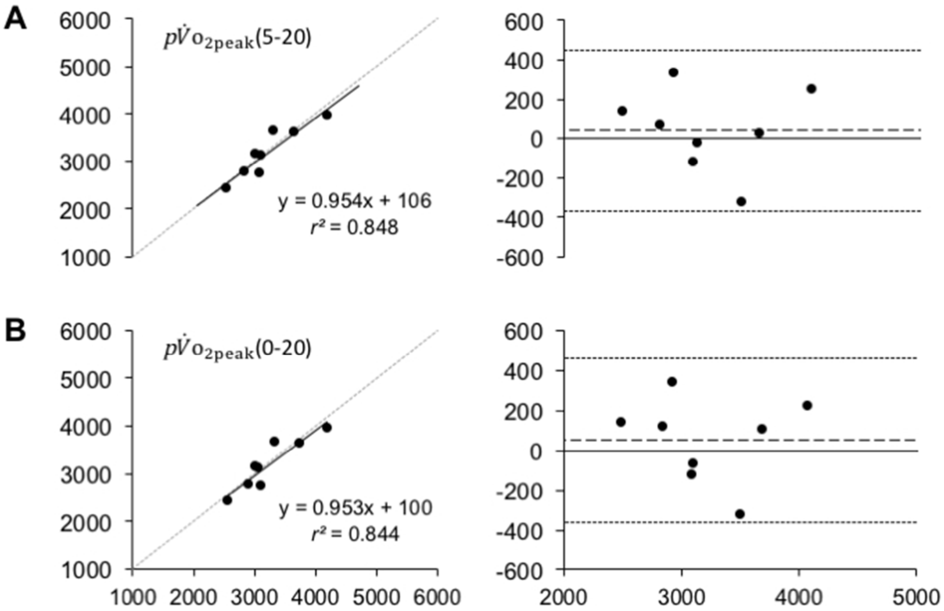

Figure 3. Series A: Comparison between VO$_2$ measured during exercise (200SS)–criterion VO$_{2peak}$(-20-0) in the x-axis–and estimated from postexercise measurements after 200TT using the HR/VO$_2$ modelling procedure: (A) pVO$_{2peak}$(5-20) and (B) pVO$_{2peak}$(0-20). The left panel shows the regression line (solid back) and the equality line (dashed grey). In the right panel, the y-axis represents the differences between estimated and measured VO$_{2peak}$ values; lines represent equality (solid), mean difference (long-dashed), and ±95% limits of agreement (short-dashed). All data are expressed in mlO$_2$·min^{-1}.
254x169mm (72 x 72 DPI)

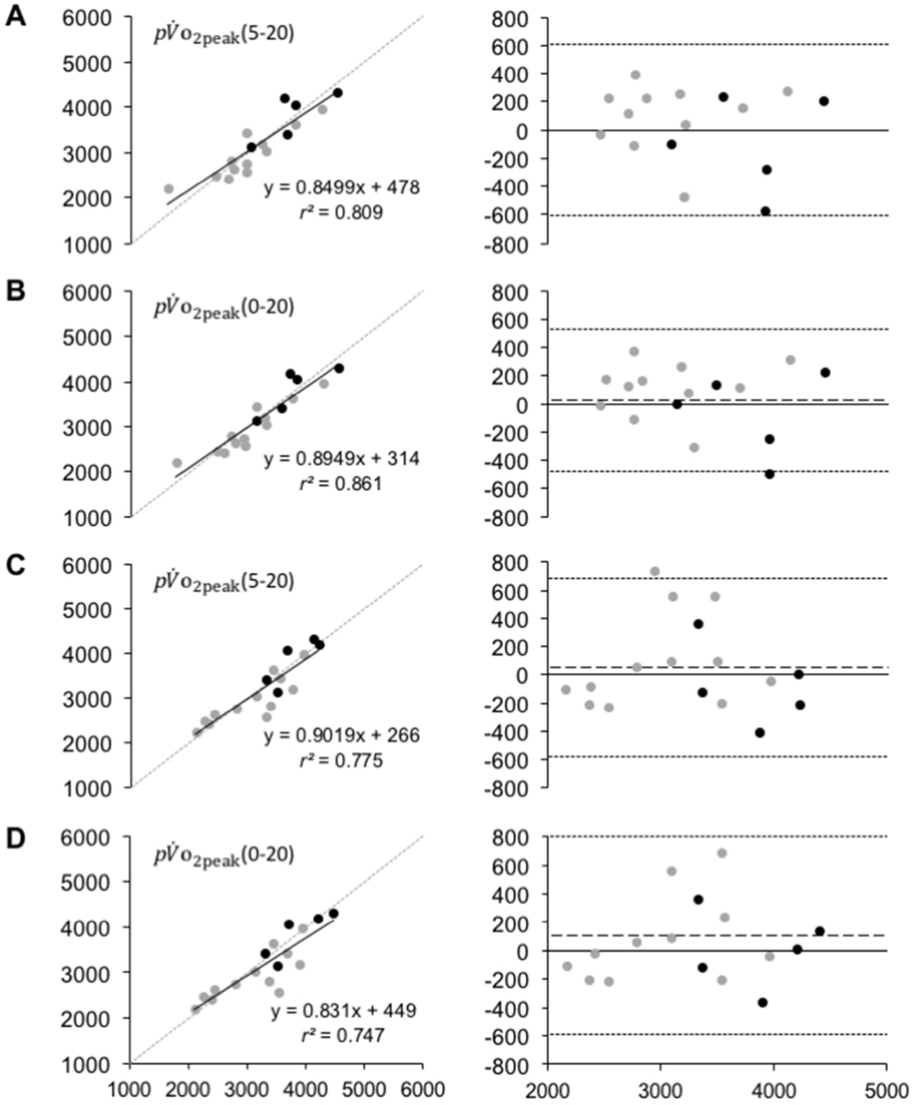

Figure 4. Series B. Comparison between the VO_2 measured during exercise (200SS)–criterion VO_{2peak}(-20-0) in the x-axis–and estimated from postexercise measurements using the HR/VO_2 modelling procedure at 200TT (A, B) and 400TT (C, D). Males (black dots) and females (grey dots) are shown separately. The remaining plot details are the same as those in figure 3.
254x294mm (72 x 72 DPI)

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

Table 2. Series A. Peak $\dot{V}\text{o}_2$ 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 $\dot{V}\text{o}_2$ (ml·min^{-1})	95% CI (ml·min^{-1})		Mean difference (ml·min^{-1})	Mean difference (%)	r^2	SE_E (ml·min^{-1})	SE_E (%)	Diff. from criterion[#] (p)
Exercise (criterion)	$\dot{V}\text{o}_{2\text{peak}}(-20-0)$	3187 ± 530	2744	3630	-	-	-	-	-	-
Linear BE	$\dot{V}\text{o}_{2\text{peak}}(0-20)$	3084 ± 518	2650	3517	-104	-3.4	0.787	264	8.3	1.000
	BE(20)	3676 ± 607	3168	4184	489	13.3	0.639	344	10.8	0.106
	BE(3∪4x20)	3448 ± 598	2949	3948	261	7.6	0.865	211	6.6	0.188
Modelling	$p\dot{V}\text{o}_{2\text{peak}}(0-20)$	3240 ± 511	2812	3667	53	1.6	0.844	226	7.1	1.000
	$p\dot{V}\text{o}_{2\text{peak}}(5-20)$	3229 ± 511	2802	3657	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.

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)
$\dot{V}o_{2\text{peak}}(-20-0)$ (criterion)	200	3192 ± 667	2850	3535	-	-	-	-		-	
$\dot{V}o_{2\text{peak}}(0-20)$	200	3055 ± 688	2701	3409	-138	-4.5	0.878	241	7.5	1.000	0.317
	400	3152 ± 729	2778	3527	-40	-1.3	0.778	325	10.2	1.000	
BE(20)	200	3332 ± 686	2979	3685	139	4.2	0.875	244	7.6	1.000	0.077
	400	3607 ± 829	3180	4033	414	11.5	0.446	513	16.1	1.000	
BE(30)	200	3358 ± 663	3017	3699	165	4.9	0.893	225	7.1	0.633	0.007*
	400	3706 ± 821	3284	4128	513	13.9	0.685	387	12.1	0.028*	
BE(3x20)	200	3442 ± 766	3048	3836	249	7.2	0.850	267	8.4	0.314	0.241
	400	3573 ± 818	3152	3993	380	10.6	0.775	327	10.2	0.093	
BE(4x20)	200	3407 ± 846	2973	3842	215	6.3	0.815	296	9.3	1.000	0.786
	400	3439 ± 828	3014	3865	247	7.2	0.809	301	9.4	1.000	
BE(3∪4x20)	200	3438 ± 795	3029	3846	245	7.1	0.846	270	8.5	0.533	0.356
	400	3547 ± 824	3123	3971	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 (m)	Peak $\dot{V}o_2$ (ml·min^{-1})	95% CI (ml·min^{-1})		Mean diff. (ml·min^{-1})	Mean diff. (%)	r^2	SE_E (ml·min^{-1})	SE_E (%)	Diff. with criterion[#] (p)	Diff. between tests[#] (p)
$\dot{V}o_{2peak}(-20-0)$ (criterion)	200	3192 ± 667	2850	3535	-	-	-	-		-	
LOG(20)	200	3350 ± 695	2992	3707	157	4.7	0.879	239	7.5	1.000	0.125
	400	3588 ± 824	3165	4012	396	11.0	0.404	532	16.7	1.000	
LOG(30)	200	3398 ± 655	3061	3735	206	6.1	0.883	235	7.4	0.179	0.010*
	400	3748 ± 845	3313	4183	556	14.8	0.651	407	12.7	0.028*	
LOG(3x20)	200	3707 ± 788	3302	4112	514	13.9	0.782	321	10.1	0.003*	0.467
	400	3808 ± 885	3353	4262	615	16,2	0.671	395	12.4	0.013*	
LOG(4x20)	200	3900 ± 965	3403	4396	707	18.1	0.739	352	11.0	0.004*	0.300
	400	3717 ± 930	3239	4196	525	14.1	0.738	352	11.0	0.042*	
LOG(3∪4x20)	200	3814 ± 899	3352	4277	622	16.3	0.759	338	10.6	0.004*	0.890
	400	3836 ± 890	3378	4293	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 ($p < 0.05$).

Table 5. Series B. Peak $\dot{V}\mathrm{o}_2$ measured during exercise (200SS) and estimated from postexercise measurements by the HR/$\dot{V}\mathrm{o}_2$ modelling procedure following the same test (SS200) and after a 400-m unimpeded swim (TT400).

Procedure	Test	Peak $\dot{V}\mathrm{o}_2$	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*)
$\dot{V}\mathrm{o}_{2\mathrm{peak}}(-20-0)$ (criterion)	200	3192 ± 667	2850	3535	-	-	-	-		-	
$p\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$	200	3217 ± 691	2861	3572	24	0.7	0.861	257	8.0	1.000	0.373
	400	3303 ± 694	2946	3659	110	3.3	0.747	346	10.9	1.000	
$p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$	200	3194 ± 706	2831	3557	2	0.1	0.809	301	9.4	1.000	0.620
	400	3245 ± 651	2911	3580	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).

Table 6. Linear regression between $\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$ 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	$\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$	y=0.908x+388	y=0.907x+421	y=0.807x+649
	BE(20)	y=0.698x+622	y=0.909x+165	y=0.537x+1256
	BE(30)	-	y=0.951x-0.3	y=0.672x+702
	BE(3x20)	-	y=0.802x+433	y=0.718x+628
	BE(4x20)	-	y=0.712x+768	y=0.725x+700
	BE(3∪4x20)	y=0.824x+345	y=0.772x+539	y=0.703x+700
Semilogarithmic BE	LOG(20)	-	y=0.899x+181	y=0.514x+1347
	LOG(30)	-	y=0.956x-58	y=0.636x+807
	LOG(3x20)	-	y=0.749x+418	y=0.617x+841
	LOG(4x20)	-	y=0.594x+877	y=0.616x+903
	LOG(3∪4x20)	-	y=0.646x+729	y=0.618x+821
Modelling	$p\dot{V}\mathrm{o}_{2\mathrm{peak}}(0-20)$	y=0.953x+100	y=0.895x+314	y=0.831x+449
	$p\dot{V}\mathrm{o}_{2\mathrm{peak}}(5-20)$	y=0.954x+106	y=0.850x+478	y=0.902x+266

See table 3,4 and 5 for Pearson coefficient of determination (r^2) and estimation bias (SEE_E)