Are Oxygen Uptake Kinetics Modified When Using a Respiratory Snorkel?

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Purpose: The aim of this study was to compare VO₂ kinetics during constant power cycle exercise measured using a conventional facemask (CM) or a respiratory snorkel (RS) designed for breath-by-breath analysis in swimming. Methods: VO₂ kinetics parameters—obtained using CM or RS, in randomized counterbalanced order—were compared in 10 trained triathletes performing two submaximal heavy-intensity cycling square-wave transitions. These VO₂ kinetics parameters (ie, time delay: td₁, td₂; time constant: τ₁, τ₂; amplitude: A₁, A₂, for the primary phase and slow component, respectively) were modeled using a double exponential function. In the case of the RS data, this model incorporated an individually determined snorkel delay (ISD). Results: Only td₁ (8.9 ± 3.0 vs 13.8 ± 1.8 s, P < .01) differed between CM and RS, whereas all other parameters were not different (τ₁ = 24.7 ± 7.6 vs 21.1 ± 6.3 s; A₁ = 39.4 ± 5.3 vs 36.8 ± 5.1 mL·min⁻¹·kg⁻¹; td₂ = 107.5 ± 87.4 vs 183.5 ± 75.9 s; A₂′ (relevant slow component amplitude) = 2.6 ± 2.4 vs 3.1 ± 2.6 mL·min⁻¹·kg⁻¹ for CM and RS, respectively). Conclusions: Although there can be a small mixture of breaths allowed by the volume of the snorkel in the transition to exercise, this does not appear to significantly influence the results. Therefore, given the use of an ISD, the RS is a valid instrument for the determination of VO₂ kinetics within submaximal exercise.

Keywords: time constant, slow component, primary phase

Initially, direct measurement of cardiorespiratory parameters in swimming was completed with the use of Douglas bag or mixing chamber methods.¹ Toussaint et al² later developed a respiratory snorkel (RS) and valve system that was shown to be valid in spite of a slight increase in drag. The RS includes a mouthpiece fixed
to a headset, and inspiratory and expiratory tubes separated by a two-way non-rebreathing valve. The expiratory tube is connected to the gas analyzer turbine, and expiratory gas is sent to the turbine and to O₂ and CO₂ sensors via a Nafion sampling line. Expiration and inspiration are delimited by means of a velocity threshold in the flow of the turbine. Keskinen et al. adapted another RS for breath-by-breath measurement and demonstrated minute ventilation (VE), oxygen consumption (VO₂), and carbon dioxide production (VCO₂) to be decreased by 3 to 5%, 5 to 7%, and 4 to 6%, respectively, when using the RS connected to a breath-by-breath (BxB) gas analyzer (K4b², Cosmed, Rome, Italy) compared with a control, conventional mask, condition. Conversely, Rodriguez et al. recently showed that although the expiratory fraction of oxygen FEO₂ was significantly larger when measured with the RS than via a mechanical gas exchange simulation system, VO₂ and VCO₂ measurements were not different. Aquatrainer (Cosmed, Rome, Italy) incorporating the same function principles and with similar dead space volume than the larger RS validated by Rodriguez et al. was later developed and information on its oxygen uptake measurements validity has not been provided.

The characteristics of the VO₂ kinetics response within constant work-rate exercise, as well as its relationship to exercise performance, have been described, particularly for cycling and running. The determination of VO₂ kinetics and, specifically, the parameters revealed by modeling the kinetics response (e.g., primary phase time constant and slow component amplitude) have been shown to be important determinants of physical performance during high-intensity exercise. Faster kinetics seem to be linked to smaller contribution of the anaerobic system via a smaller O₂ deficit and less accumulation of metabolic fatiguing products. Furthermore, in events lasting 1 to 15 minutes, such as the majority of swimming events, VO₂ kinetics seems to be an important and useful parameter for coaches to evaluate, especially in elite athletes.

At high exercise intensities, VO₂ kinetics parameters are influenced by exercise mode. For example, the time constant of the primary phase appears to be faster in running than in cycling, possibly as a result of differences in muscular action. Nevertheless, limited breath-by-breath analyses have been conducted, using the RS in swimming exercise.

It is possible that the use of the RS may modify the VO₂ kinetics. The enlargement of the respiratory dead space that is induced by the RS amplifies the difficulty of performing gas exchanges, and requires an increase in tidal volume so as to maintain alveolar volume. The rebreathing of the expired air, although minimized by the two-way valve could induce higher values of VE, VO₂ and VCO₂ due to higher PCO₂ values in the blood.

Alternatively, it may engender an increase in parameter variability (due to increased errant breaths, the shape of the mouthpiece, the distance to the turbine, the outlet tube volume, and/or the inlet tube volume) and thus a potential need to adjust the modeling procedure that is used for the VO₂ kinetics data so obtained.

Therefore, it is important to determine the characteristics of VO₂ kinetics at the onset of exercise, while using the RS and applying appropriated mathematical modeling of the VO₂ response. The determination of VO₂ kinetics at the onset of swimming exercise, and the comparison of such data with that obtained from other terrestrial activities such as running or cycling, will only be possible after the validation of the RS.
The aim of this study, therefore, was to compare the respiratory and O₂ kinetics parameters obtained within a heavy intensity constant-load cycling test when using a conventional facemask (CM) to those obtained when using a RS.

Methods

Subjects

Ten trained male triathletes (age 29.3 ± 8.3 y; height 1.77 ± 0.07 m; mass 67.5 ± 7.3 kg) gave their written informed consent to participate in the study, which was granted ethical approval by the Scientific Committee of the Faculty of Human Kinetics of the Technical University of Lisbon.

Design Study

Each participant performed both a CM and RS (Aquatrainer, Cosmed, Rome, Italy) trial, a week apart, in randomized counterbalanced order. The athletes were instructed not to exercise within the 24 h period preceding each trial.

Methodology

The expiratory tube of the RS had a length of 1.83 m and internal diameter of 0.286 m, and the two-way non-rebreathing valve separating the inspiratory and expiratory tube had a volume of 45 mL. The inspiratory and expiratory resistances were minimal (9 cm H₂O at 100 L·min⁻¹). The CM and RS were connected to a portable breath-by-breath cardiorespiratory gas analyzer (K4b², Cosmed, Rome, Italy), calibrated according to the manufacturer’s instructions, immediately before each test.

The participants first performed a continuous incremental test to exhaustion (involving stage increments of 30 W every minute) on a cycle ergometer (Monark, Stockholm, Sweden), for the determination of both peak oxygen uptake (VO₂peak) and the ventilatory threshold (VT₁). During the incremental test, the breath-by-breath gas samples were averaged every 30 s. VO₂peak was then recorded as the highest 30-s average of VO₂ (mL·kg⁻¹·min⁻¹). Peak power output (PPO, watts) was estimated as that corresponding to the last full exercise stage that was performed. The VT₁ was established as the power at which VE/VO₂ and end-tidal O₂ pressure (PETO₂) began to increase without a simultaneous increase in end tidal CO₂ pressure (PETO₂).¹⁸

Following one hour of seated rest, the participants underwent two 8 min square-wave transitions from rest to the power output corresponding to 25% Δ [= VT₁ + 0.25 × (VO₂peak – VT₁)]. Between the two bouts of constant power exercise, the participants underwent one hour of passive rest.

The rest between bouts were established so as to not influence the VO₂ kinetics of the subsequent bout.¹⁹

The data obtained from the two exercise transitions were linearly interpolated at 1 s intervals, time aligned to the onset of exercise, and ensemble averaged to provide a single on transient for each participant for each of the CM and RS conditions. To ensure that the early initial component did not influence the kinetics parameters of the primary component, the first 20 s of data were removed from subsequent analyses.
We used a double component exponential model to describe the VO$_2$ kinetics obtained during the constant-load test:

$$VO_2(t) = VO_2_{\text{base}} + A_1 \cdot (1 - e^{-(t-td1)/\tau_1}) \cdot U_1 \quad \text{Phase 2 (Primary component)}$$

$$+ A_2 \cdot (1 - e^{-(t-td2)/\tau_2}) \cdot U_2 \quad \text{Phase 3 (Slow component)}$$

Where $U_1 = 0$ for $t < td1$ and $U_1 = 1$ for $t > td1$, and $U_2 = 0$ for $t < td2$ and $U_2 = 1$ for $t > td2$.

Each component was described by a time delay ($td1$ and $td2$), by a time constant ($\tau_1$ and $\tau_2$) and by an amplitude ($A_1$ and $A_2$). These parameters were calculated, by an iterative procedure, by minimizing the sum of the mean squares of the differences between the modeled and the measured VO$_2$ values.

Because the asymptotic value of the second function is not necessarily reached at the end of the exercise, the relevant amplitude of the VO$_2$ slow component was defined as

$$A_2 = A_2 \cdot (1 - e^{-(te-td2)/\tau_2})$$

where $te$ was the time at the end of the exercise bout.

In the RS condition, the time delay of the primary component was imposed to be superior to the individual snorkel delay (ISD) ie, the time necessary for the first exercise breath to reach the analyzer. The ISD was determined to cope with the delay introduced by the long tubing and to assure that breath-by-breath data are aligned with the onset of swimming exercise. This time was calculated for each athlete repetition as the difference between the onset of exercise ($t_s$) and the time ($t_{ISD}$) when the following breaths summed a tidal volume (TV) superior to the outlet tube volume (RSV), ie, when the VO$_2$ data so obtained could be considered to be representative of the exercise task.

We defined ISD by $t_{isd} - t_s$ where $t_{isd}$ is the smaller time such that

$$\sum_j^j TV(tj) \geq RSV$$

**Statistical Analysis**

A paired-sampled Student’s $t$ test was used to identify any differences between the RS and CM conditions in VO$_2$ kinetics parameters during the constant-load exercise task. The differences between the measurements performed with the two devices were drawn in relation to the mean value and 95% of the differences were expected to lie between the two “limits of agreement” that were the mean difference $\pm$ 2 SD of the differences, expressed as bias $\times \div$ random error. Statistical significance was accepted when $P < .05$.

**Results**

None of the following maximal respiratory parameters, as obtained within the incremental exercise test, differed significantly between the CM and RS conditions: VO$_2$peak (55.5 $\pm$ 2.7 vs 53.1 $\pm$ 3.3 mL·min$^{-1}$·kg$^{-1}$, $P = .07$; bias $\times \div$ random error,
1.04 $\div 1.12$); respiratory frequency ($53.6 \pm 11.0$ vs $49.9 \pm 8.6$ cycle-min$^{-1}$, $P = 0.21, 1.07 \div 1.29$); tidal volume ($2.9 \pm 0.3$ vs $2.9 \pm 0.5$ l, $P = .96, 1.00 \div 1.12$); and minute ventilation ($151.2 \pm 24.0$ cycle-min$^{-1}$ vs $140.3 \pm 7.0$, $P = .19, 1.07 \div 1.16$).

As regards the oxygen uptake kinetics parameters for the square wave transitions, and the residuals resulting of the modeling process associated with it, the only significant difference between the two conditions was the higher $td_{1}$ observed in the RS condition ($P = .003$). The coefficient of determination of the modeled VO$_{2}$ did not differ between the two situations (Table 1).

Table 1  Mean ($\pm$SD), mean difference ($\pm$SD) and bias $\div$ random error of the parameters of the VO$_{2}$ kinetics during a transition from rest to an 8 min constant-power exercise, measured either with a conventional mask (CM) or a respiratory snorkel (RS) ($n = 10$)

<table>
<thead>
<tr>
<th>Variable</th>
<th>CM</th>
<th>RS</th>
<th>Mean difference</th>
<th>Positive bias $\div$ random error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$ (mL·kg$^{-1}$·min$^{-1}$)</td>
<td>$39.4 \pm 5.3$</td>
<td>$36.8 \pm 5.1$</td>
<td>$2.6 \pm 5.0$</td>
<td>$1.07 \div 1.26$</td>
</tr>
<tr>
<td>$td_{1}$ (s)</td>
<td>$8.9 \pm 3.0$</td>
<td>$13.7 \pm 1.6$</td>
<td>$-4.8 \pm 3.7$</td>
<td>$0.58 \div 1.66$</td>
</tr>
<tr>
<td>$\tau_{1}$ (s)</td>
<td>$24.7 \pm 7.4$</td>
<td>$21.1 \pm 6.3$</td>
<td>$3.6 \pm 5.3$</td>
<td>$1.16 \div 1.46$</td>
</tr>
<tr>
<td>$A'_2$ (mL·kg$^{-1}$·min$^{-1}$)</td>
<td>$2.6 \pm 2.4$</td>
<td>$3.1 \pm 2.6$</td>
<td>$-0.5 \pm 2.4$</td>
<td>$0.82 \div 2.68$</td>
</tr>
<tr>
<td>$%A'_2$</td>
<td>$5.7 \pm 4.9$</td>
<td>$7.2 \pm 5.7$</td>
<td>$-1.5 \pm 5.4$</td>
<td>$0.77 \div 2.67$</td>
</tr>
<tr>
<td>$td_{2}$ (s)</td>
<td>$107.5 \pm 87.4$</td>
<td>$183.5 \pm 75.9$</td>
<td>$-76.0 \pm 96.9$</td>
<td>$0.48 \div 2.33$</td>
</tr>
<tr>
<td>$r^2$</td>
<td>$0.83 \pm 0.08$</td>
<td>$0.88 \pm 0.17$</td>
<td>$0.05 \pm 0.18$</td>
<td></td>
</tr>
<tr>
<td>Sum of residuals</td>
<td>$-16.1 \pm 27.1$</td>
<td>$-3.5 \pm 28.0$</td>
<td>$12.6 \pm 28.4$</td>
<td></td>
</tr>
<tr>
<td>ISD (s)</td>
<td>$4.6 \pm 1.2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End-exercise VO$<em>{2}$ (%VO$</em>{2\max}$)</td>
<td>$83.2 \pm 6.8$</td>
<td>$83.3 \pm 12.4$</td>
<td>$-0.1 \pm 12.7$</td>
<td>$1.00 \div 1.31$</td>
</tr>
</tbody>
</table>

Note. Time delay ($td_{1}$, $td_{2}$), time constant ($\tau_1$, $\tau_2$), amplitude ($A_1$, $A_2$) of the primary phase and slow component, respectively, $A'_2$ value of slow component at the end of exercise, $%A'_2 = A'_2 / (A_1 + A'_2)$; $r^2$: coefficient of determination between the breath-by-breath data and the modeled VO$_{2}$; sum of the residuals resulting of the model; ISD: individual snorkel delay. End-exercise VO$_{2}$: oxygen uptake measured at the end of the constant load exercise in relation to the VO$_{2}$ peak attained within the incremental test; $^a$ Significant difference between conventional mask and respiratory snorkel ($P < .01$).

**Discussion**

The aim of this study was to compare the respiratory and VO$_{2}$ kinetics parameters obtained within a heavy intensity constant-load cycling test when using a CM to those obtained when using a RS. The VO$_{2}$ response measured with a respiratory snorkel in either incremental or constant load exercise was not different from similar measurements performed with a conventional facemask.
Our results for the incremental cycle test did not confirm the decrease in minute ventilation with the use of RS that has been described in the literature. However, the nonsignificant underestimation of VO₂ that we did observe in the current study was almost constant \( y = 0.96x - 135 \) over the range of intensities that were covered by the incremental test (Figure 1). Therefore, during a rest-to-exercise transition, we would expect that the amplitude of the primary phase (A1) could be affected by the use of a RS due to the lower ventilation. Although there are considerable interindividual variations and the mean difference indicates a slight underestimation of both A, and τ1, this difference is not statistically significant. As for the remaining VO₂ kinetics parameters within the submaximal cycling trials, only td1 was significantly different between the CM and RS conditions. This may be explained by the delay introduced by the volume of the tube, and by the subsequent introduction of the ISD into the modeling procedure. This delay did not apparently interfere with the determination of the other kinetics parameters that were assessed by this study, namely τ1 and A, as shown in Figure 2 displaying sample data of a subject.

The similarity of the τ1 values between RS and CM, along with the agreement of these values with data that have been previously obtained by other authors under similar conditions, supports our premise that the use of a RS does not significantly affect VO₂ kinetics. Our results also agree with the validity data that Rodriguez et al. obtained comparing a similar RS with a mechanical gas exchange simulation system. Although there can be a small mixture of breaths allowed by the volume of the snorkel in the transition to exercise, this does not appear to significantly influence the results. Moreover, the introduction of the ISD into the algorithm appears to provide a satisfactory method of coping with the delay introduced by the volume of the RS tube.

**Figure 1** — Regression analysis of the oxygen uptake VO₂ (mL·min⁻¹) during the incremental exercise test (30 s average) with the conventional face mask (CM) and the respiratory snorkel (RS). n = 10. The identity line is represented by a dashed line.
As the validity of similar respiratory snorkels in constant and incremental exercise was demonstrated by previous studies, fast transitions between work loads seem to be the most problematic issue regarding the possibility of inadequacy of breath-by-breath measurements involving the swimming snorkel. However, at the intensities performed in the current study, the tidal volumes expired by the participants exceeded the RS expiratory tube volume within seconds, and oxygen uptake kinetics parameters were unaffected.

The coefficient of determination of either the modeled VO\textsubscript{2} or the residuals did not differ between the CM and RS conditions. The RS with the introduction of ISD does not adversely affect the adequacy of the modeling procedure.

Methodological constraints prevent the reproduction of this study in swimming, because it is not currently possible to collect breath-by-breath data using a CM in water exercise. The physiological responses within swimming exercise are expected to differ from those seen within cycling exercise due to, for example, the effects of the supine position that is adopted\textsuperscript{22} or the thermoregulatory response,\textsuperscript{23} on the VO\textsubscript{2} kinetics. However, this paper discloses that RS results could be compared with CM data as regards VO\textsubscript{2} kinetics, and therefore opens the door for valid comparison between swimming and terrestrial activities.

**Conclusion**

The use of a respiratory snorkel, with the introduction of the ISD in the modeling, did not influence the determination of VO\textsubscript{2} kinetics parameters within the transition from rest to a constant load submaximal exercise. Therefore, direct measurement of VO\textsubscript{2} for estimating VO\textsubscript{2} kinetics in swimming would not be modified by the use of RS.
Practical Implications

The use of a respiratory snorkel allows for:

- Direct determination of VO2 kinetics in swimming;
- The comparison of VO2 kinetics parameters in swimming with those obtained within terrestrial sports such as cycling or running;

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