Comparison between different methods of analysis of slow component of oxygen uptake: a view in severe exercise domain

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ABSTRACT

The objective of the present study was to compare in severe exercise domain, different techniques used for measuring the amplitude of the slow component (SC) of oxygen uptake kinetics. Ten trained cyclists, male (age: 25 ± 3.6 years, body mass: 67.2 ± 4.5 kg, height: 174.8 ± 6.5 cm and $\dot{V}O_{2max}$: 62.4 ± 3.1 mL.kg^{-1}.min^{-1}), performed two identical bouts transitions at constant load [mean ± SD (intensity 75%Δ: 75% of the difference between the $\dot{V}O_2$ lactate threshold and the $\dot{V}O_{2max}$)] in different days. The SC was calculated from different methods: (1) bi-exponential model [$\dot{V}O_2(t) = \dot{V}O_{2base} + A_1 (1 - e^{-(t-TA1/\tau 1)}) + A_2 (1 - e^{-(t-TA2/\tau 2)})$], (2) predetermined intervals ($\Delta\dot{V}O_{2\,6\text{-}2}$: difference between the second min $\dot{V}O_2$ and the end $\dot{V}O_2$; $\Delta\dot{V}O_{2\,6\text{-}3}$: difference between the third min $\dot{V}O_2$ and the end $\dot{V}O_2$) and (3) difference between the end $\dot{V}O_2$ and the value obtained from a mono-exponential adjustment of the "primary component" (predetermined time of 120 s) ($SC_{6\text{-}\text{"PC"}}$). All the methods were compared among themselves. The results showed a significant underestimation of the SC obtained by method of predetermined intervals ($\Delta\dot{V}O_{2\,6\text{-}2}$: 432 ± 126 ml.min^{-1} and $\Delta\dot{V}O_{2\,6\text{-}3}$: 279 ± 88 ml.min^{-1}) when compared with bi-exponential model (676 ± 136 ml.min^{-1}) and $SC_{6\text{-}\text{"PC"}}$ [(719 ± 265 ml.min^{-1} ($p < 0.05$))]. There was not significant difference among the other comparison. The results suggest that the use of predetermined time may underestimate the SC when compared with bi-exponential model and $SC_{6\text{-}\text{"PC"}}$.

Keywords: Kinetics. Oxygen uptake. Cyclists. Lactate. Bi-exponential model.

INTRODUCTION

The response of the oxygen uptake ($\dot{V}O_2$) in the transition from rest or mild exercise to the exercising condition (moderate, intense, very intense and supramaximal) at steady load has been described in the literature[1-3]. In the beginning of the exercise (after phase I 'cardiodynamic' – 15 to 20 initial seconds) performed at moderate intensity (i.e., below the lactate threshold – LT), the $\dot{V}O_2$ increases according to a mono-exponential model (Phase 2) in order to reach a new steady state (Phase 3) within 2 to 3 min. On the other hand, during intense and very intense exercises (above the LT), the $\dot{V}O_2$ kinetics primary component is supplemented by an additional slow component (SC), which causes an increase in the $\dot{V}O_2$ and, consequently, a delayed and increased steady state, being able to reach values of oxygen maximal uptake ($\dot{V}O_{2max}$)[1,3]. During exercises of steady load at intense domain [intensities between the LT and the Lactate Maximal Steady State (LMSS)] the SC estabilizes during exercise, but during exercises called very intense (intensities between the LMSS and the $\dot{V}O_2$) the SC progressively increases and can reach the $\dot{V}O_{2max}$[4-5].

The SC may be calculated through mathematical models, which allow the identification and measurement of the breadth magnitude[2,6]; or through pre-set intervals ex.: $\Delta\dot{V}O_{2\,6\text{-}3}$: difference of the $\dot{V}O_2$ between the third and sixth minute of exercise[1,7-11] or $\Delta\dot{V}O_{2\,6\text{-}2}$: difference of the $\dot{V}O_2$ between the second and sixth minute of exercise[12]. These last kinds of analysis simplify the procedures; however, they can generate data which do not reflect the suitable behavior of the studied phenomenon. Within this context, Bearden and Moffatt[13] in a study with cyclists have observed that SC values obtained from pre-set intervals ($\Delta\dot{V}O_{2\,6\text{-}3}$), during intense exercise (Δ30%: 30% of the difference between the $\dot{V}O_2$ in the LT and the $\dot{V}O_{2max}$), presented lower breadths when compared with data obtained by the adjustment mathematical model. Nevertheless, analyses similar to the one by Bearden and Moffatt[13] have not been performed yet in a domain of very intense intensity (intensities where there is not a SC stabilization).

Recently, Burnley *et al.*[14] have used another mathematical model to calculate the SC. Such model was adopted from the study by Rossiter *et al.*[15] and had as proposal the adjustment of the primary component from an interval of steady time (120 s). In that analysis, the SC was calculated by the difference between the mean value of the last seconds of exercise and the adjusted value of the 'primary component' ($SC_{6\text{-}\text{"PC"}}$). The possible differences between this model and the remaining have been investigated. According to Bearden and Moffatt[13], different methods of SC analyses may result in different breadths. Therefore, the aim of this study was to compare different methods of SC analysis during very intense exercise (75%Δ-75% of the difference between the $\dot{V}O_2$ in the LT and the $\dot{V}O_{2max}$).

METHODS

Ten trained male cyclists participated in the study (age: 25.0 ± 3.6 years, body weight: 67.2 ± 4.5 kg and height: 174.8 ± 6.5 cm). The mean weekly distance completed by the volunteers was of 378 ± 60.4 km and the experience in competitions of 4.6 ± 2.1 years. All volunteers were informed on the aim of the research, as well as its possible risks and benefits. After agreeing with the study's proposal and all the experimental procedures having been approved by the Ethics Committee from the Federal University of São Paulo (nº 1246/03), the participants signed a Free and Clarified Consent Form. The inclusion criteria were: (a) trained male cyclists,

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(b) age range of 20-35 years, (c) weekly training volume of at least 250 km/week and (d) minimum experience of 1 year in national competitions. Electrocardiogram examinations were performed (rest and effort) one week after the beginning of the experiment.

Experimental protocol

The participants visited the laboratory in four distinct occasions, during a period of two weeks. In the first visit, they were familiarized with the cycle-ergometer and remining experimental procedures. In the second visit, they performed a load incremental test until voluntary exhaustion, with the purpose to evaluate the LT and the $\dot{V}O_{2max}$. In the third and fourth visits, the volunteers performed two steady load transitions [$75\%\Delta = \dot{V}O_2$ LT + 0.75 x ($\dot{V}O_{2max} - \dot{V}O_2$ LT)]. The load concerning this exercise intensity was determined by linear regression, from $\dot{V}O_2$ values and power, which were obtained during each stage of the incremental test.

The participants were told to arrive at the laboratory 1 h before the established time, well-hydrated and not having taken alcohol, caffeine or any kind of supplementation in the days of the test. They were also asked to avoid extenuant physical exercises in the 24 hours prior to the tests. A minimum interval of 48 h was required between each visit.

All tests were performed in a mechanical cycle ergometer (Monark 834 E, Ergomedic, Sweden). The seat's height and handle's position were registered in the first visit and repeated in the following tests' sessions. The ventilatory variables were determined, breath after breath, by an open circuit computerized test system (Sensor Medics – Vmax 29 series – Metabolic Measument Cart, Yorba Linda, CA). The measurement of the expiratory flow was performed by a sensor of mass flow (anemometer), calibrated before each test session, by a 3-liter serynge, in three different flow levels. A Hans Rudolph flow-by face mask (Kansas City, MO USA) was used for collection of expired gases. The analysis systems of the O_2 and CO_2 were calibrated before each session, using the room air and the concentration of known gases (16% of O_2 and 4% of CO_2). The HR was registered at each 5 s, during all tests, by telemetry (Polar, Advantage NV).

In order to determine the $\dot{V}O_{2max}$ and the LT, the participants performed a progressive continuous test, with initial load of 105 W and increments of 35 W at each 3 minutes, keeping a steady cadence of 70 rpm[16]. At the end of each stage, a blood sample from the earlobe was collected (25 μl) in order to determine the blood lactate concentration [La]. The LT was determined by the visual method ([La] x power) and defined as the exercise intensity prior to the first one and keeping increase of [La] above the rest concentrations[17]. As analysis criterium, two independent and experienced observers were consulted. There was an agreement from the observers part on the point in which the LT for all volunteers occurred. The $\dot{V}O_{2max}$ was defined as the highest value of $\dot{V}O_2$, measured in 20 s-intervals, during the incremental test. All volunteers completed at least two of the following criteria for $\dot{V}O_{2max}$: (1) one rate of gas exchange > than 1.1, (2) one [La] peak > than 8 mmol.l^{-1}, and (3) one peak hear rate ≥ 90% of the maximal value expected for the age[18].

In the third and fourth visits, the volunteers performed steady load transitions which were initiated with a period of 4 min, pedaling in a mild load (35 watts), followed by a sudden load application, for a period of 6 min (intensity of 75%Δ). The cadence was kept steady at 70 rpm. The use of two days for performance of the steady load transitions, following the recommendations by Lamarra *et al.*[19], had as aim to increase data reliability.

$\dot{V}O_2$ kinetics analysis

For each mild load transition for exercise, the $\dot{V}O_2$ data (breath after breath) were linearly interpolated in order to obtain values with 1 s intervals. The data concerned with the two transitions were aligned, and later, the means for the $\dot{V}O_2$ values were calculated. This procedure had as objective to diminish the 'noise' and accentuate the physiological responses characteristics. The baseline $\dot{V}O_2$ ($\dot{V}O_{2\,base}$) was defined as the mean value of the 4 initial minutes (pedaling at light load). The first 20 s of exercise ('cardiodynamic' Phase I) have not been included in the adjustment model. The $\dot{V}O_2$ response, after the 20 s of exercise, was described from the two exponential components. Each mean response was described using the following equation[2]:

$$\dot{V}O_2\,(t) = \dot{V}O_{2\,base} + A_1\,(1 - e^{-(t-TA1/\tau1)}) + A_2\,(1 - e^{-(t-TA2/\tau2)}) \qquad \text{Equation 1}$$

The exponential model included breadths (A_1 and A_2), time constants (τ_1 and τ_2) and delayed times (TA_1 and TA_2). In order to determine the parameters of the best adjustments of the curves, a non-linear algorhytm of the minimum squares has been used (MatLab, version 6.5) which adopted the minimization of the sum of square errors as converging criterium. The A_1, to τ_1 and the TA1 described the parameters concerned with the primary component, while the A_2, to τ_2 and the TA_2 described the parameters concerned with the SC of the $\dot{V}O_2$. Since the A_2 asintote value may represent a higher value than currently reached in the end of the 6 min of exercise, the SC value was defined as A_2'.

In order to obtain the other values concerning the SC, pre-set intervals of time have been adopted, the $\Delta\dot{V}O_{2\,6\text{-}3}$: difference between the $\dot{V}O_2$ values in the third (mean of the 20 initial s) and the sixth one (mean of the 20 final s) minutes of exercise[1] and the $\Delta\dot{V}O_{2\,6\text{-}2}$: difference between the $\dot{V}O_2$ values in the second (mean of the 20 initial s) and sixth (mean of the 20 final s) minutes of exercise[12]. Besides these, the SC was obtained from the model used by Burnley *et al.*[14] and adopted by Rossiter *et al.*[15]. In this model, the primary component was adjusted through a steady time (120 s). The first 20 s of exercise ('cardiodynamic' phase) have been excluded from the adjustment. The equation used was the following:

$$\dot{V}O_2\,(t) = \dot{V}O_{2\,base} + A\,(1 - e^{-(t-TA/\tau)}) \qquad \text{Equation 2}$$

SC was calculated as the difference between the mean value of the last 20 seconds of exercise and the value of the 'primary' breadth (120 initial s of exercise), obtained by the mono-exponential adjustment ($SC_{6\text{-}\text{“PC”}}$).

Statistical procedures

The data are presented as mean ± standard deviation (SD). The *Kolmogorov-Smirnov* test was adopted for the verification of the sample's data normality and for comparison between the different methods of SC analysis, the variance analysis for repeated measurements (*ANOVA*) was applied. The *Tukey* Test was used to verify the position of the differences. The *Pearson* Correlation was used in order to verify the relationship between the different models. The statistical analyses were performed by the *STATISTICA* sofware (Statsoft, Inc, version 6.0). A significance level of $p < 0.05$ was established. The accuracy of the curve adjustments procedure was evaluated by the calculation of the determination coefficient (r^2).

RESULTS

The mean value of the $\dot{V}O_{2max}$ in the incremental test was of 62.4 3.1 ml.kg^{-1}.min^{-1} and the LT occurred at 66.3 ± 7.4% $\dot{V}O_{2max}$. The maximal power reached was 339 ± 33 watts, the [La] peak was 9.3 ± 2.1 mmol.l^{-1} and the maximal HR was 188 ± 6 bpm. The $\dot{V}O_2$ concerning the 75%Δ in the end of the exercise was of approximately 95% of the $\dot{V}O_{2max}$.

The SC breadths determined by the different methods and the remaining parameters obtained with the bi-exponential adjustment are presented in table 1. Figure 1 illustrates a bi-exponential adjustment of the $\dot{V}O_2$ of a volunteer representative of the study.

TABLE 1
Parameters of the kinetic response of the oxygen uptake during very intense exercise (mean ± S.D.)

Variables	
$\dot{V}O_{2\,base}$ (ml.min^{-1})	667 ± 167
TA_1 (s)	16 ± 2
A_1 (ml.min^{-1})	2,659 ± 326 bcd
τ_1 (s)	21 ± 4
TA_2 (s)	79 ± 19
A_2' (ml.min^{-1})	671 ± 130
τ_2 (s)	181 ± 72
$A_{2\,min}$ (ml.min^{-1})	3,592 ± 372 ad
$A_{3\,min}$ (ml.min^{-1})	3,766 ± 360 ad
$A_{\text{“CP”}}$ (ml.min^{-1})	3,361 ± 491 abc
$\Delta\dot{V}O_{2\,6\text{-}2}$ (ml.min^{-1})	457 ± 145 #
$\Delta\dot{V}O_{2\,6\text{-}3}$ (ml.min^{-1})	282 ± 84 #
$SC_{6\text{-“CP”}}$ (ml.min^{-1})	687 ± 272

$\dot{V}O_{2\,base}$, baseline value of the oxygen uptake; τ_1 and τ_2 are the time constants; TA_1 and TA_2 are the time delays; A_1, asintote breadth of the primary phase; A_2', the SC value at the end of exercise obtained by the bi-exponential adjustment; $A_{2\,min}$: breadth concerning the second minute of exercise; $A_{3\,min}$: breadth concerning the third minute of exercise; $A_{\text{“PC”}}$: breadth concerning the 'primary component' adjusted with steady time of 120 s; $\Delta\dot{V}O_{2\,6\text{-}2}$: difference between the second and sixth minute of exercise; $\Delta\dot{V}O_{2\,6\text{-}3}$: difference between the third and sixth minute of exercise; $SC_{6\text{-“PC”}}$: difference between the 'primary' breadth value (120 initial s of exercise) and the sixth minute of exercise.
a significantly different from the A_1 ($p < 0.05$).
b significantly different from the $A_{2\,min}$ ($p < 0.05$).
c significantly different from the $A_{3\,min}$ ($p < 0.05$).
d significantly different from the $A_{\text{“PC”}}$ ($p < 0.05$).
significantly different from the A_2' ($p < 0.05$).

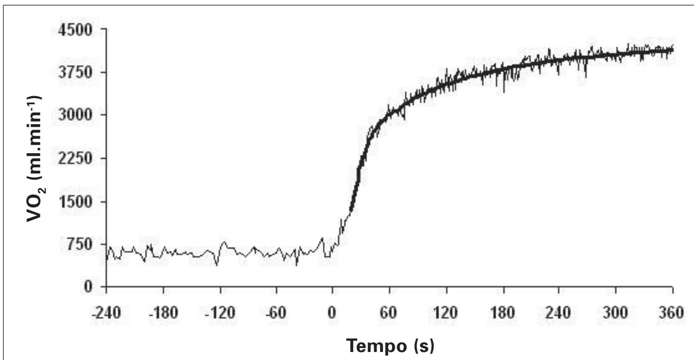

***Figure 1** – Response of the of a subject representative (adjusted from a bi-exponential model) performing exercise at very intense domain (75%Δ)*

The outcomes of this study demonstrated that the SC determined from the $\Delta\dot{V}O_{2\,6\text{-}2}$: 432 ± 126 ml.min^{-1} and the $\Delta\dot{V}O_{2\,6\text{-}3}$: 279 ± 88 ml.min^{-1} were significantly lower (31.8 and 57.9%, respectively) than the SC breadth obtained by the bi-exponential adjustment (A_2': 676 ± 136 ml.min^{-1}; $p < 0.05$). The $SC_{6\text{-“PC”}}$ (719 ± 265 ml.min^{-1}), which used a steady time for adjustment of the primary component, was not significantly different from A_2'. There was a positive statistically significant correlation between $\Delta\dot{V}O_{2\,6\text{-}2}$ and the $\Delta\dot{V}O_{2\,6\text{-}3}$ ($r = 0.79$). The remaining correlations (A_2' versus $\Delta\dot{V}O_{2\,6\text{-}2}$: $r = 0.07$; A_2' versus $\Delta\dot{V}O_{2\,6\text{-}3}$: $r = 0.11$; A_2' versus $SC_{6\text{-“PC”}}$: $r = -0.43$; $SC_{6\text{-“PC”}}$ versus $\Delta\dot{V}O_{2\,6\text{-}2}$: 0.58; $SC_{6\text{-“PC”}}$ versus $\Delta\dot{V}O_{2\,6\text{-}3}$: $r = 0.21$) were not statistically significant. The mean value found for the r^2 was of 0.97, which showed a good adjustment o the bi-exponential model for the $\dot{V}O_2$ data.

DISCUSSION

The main finding of this study was that the SC magnitude, when analyzed from pre-set time intervals ($\Delta\dot{V}O_{2\,6\text{-}2}$ and $\Delta\dot{V}O_{2\,6\text{-}3}$), during exercises performed in very intense domain (75%Δ) was underestimated when compared with the bi-exponential models[2] and $SC_{6\text{-“PC”}}$[14]. The outcomes concerning the comparison between the bi-exponential model and the $\Delta\dot{V}O_{2\,6\text{-}3}$ are in agreement with the findings by Bearden and Moffatt[13], which found similar effects in exercises performed in intense domain (30%Δ).

During the last decades, mathematical models have been developed and improved with the aim to investigate the kinetics response of oxygen uptake[2,6]. Several methodologies have been used in order to determine the SC during the years[1-2,12]. Initially, Whipp and Wasserman[1] proposed the use of the $\Delta\dot{V}O_{2\,6\text{-}3}$ as a means to quantify the SC. Later, Barstow *et al.*[2] proposed the bi-exponential adjustment mathematical model as an important tool in the determination of the SC magnitude and it has become a widely used model over the years. More recently, in the trial to readapt the way of calculating the SC with pre-set time ($\Delta\dot{V}O_{2\,6\text{-}3}$), Koppo and Bouckaert[12] used the $\Delta\dot{V}O_{2\,6\text{-}2}$, based on previous data that the SC appearance could occur in time lower than 3 min (approximately from 70 to 120 s). Within this context, the present study demonstrated that even when using $\Delta\dot{V}O_{2\,6\text{-}2}$ the SC outcomes have been underestimated (31.8%) when compared with the bi-exponential adjustment model. The same situation occurred with the $\Delta\dot{V}O_{2\,6\text{-}3}$, which was underestimated in 57.9%. A possible justification for this result is the early appearance of SC, which in the present study had a mean of 74 s and a breadth of 58-95 s. Similar delay times for the beginning of the SC (TA_2) have been described in the literature[20]. Barstow *et al.*[20] in a study with trained and non-trained individuals suggest that the TA_2 does not depend on physical aptitude. Moreover, other studies demonstrate that the TA_2 also depends on the intensity of the exercise[21-25]. Thus, the results found in the present study suggest that this differentiated behavior of the SC may be present in other exercise intensities and among other populations. Another factor which could have generated the differences between the analyses is the time constant of the SC (τ_2), which reflects the change rate in the $\dot{V}O_2$ concerned with the time, a factor which is not considered in the analysis with pre-set time. As suggested in the previous study by Bearden and Moffatt[13], the TA_2 and the τ_2 responses are factors which may have significantly influenced the differences found between the analyzed models.

The $SC_{6\text{-“PC”}}$ adapted model by Rossiter *et al.*[15] was recently used by Burnley *et al.*[14] with the purpose to detect small breadths of the SC, in a protocol used to study the SC attenuation in response to the practice of previous exercise. In the present study, the $SC_{6\text{-“PC”}}$ values were similar to the values found by the bi-exponential adjustment model; on the other hand, they were statistically different from the analysis methods with pre-set interval (table 1). This second result may have been explained by the significant difference found between the 'primary breadth' obtained with the mono-exponential of the 120 initial s of exercise (3361 ± 491 ml.min^{-1}) and the breadth of the second (3592 ± 372 ml.min^{-1}) and third (3766 ± 360 ml.min^{-1}) minute of exercise ($p < 0.05$), values which are crucial for the SC calculation in these models. Another important point to be highlighted is the low correlation between the results obtained by the $SC_{6\text{-“PC”}}$ models and bi-exponential adjustment ($r = -0.43$). This low correlation suggests that these analyses may not reflect the same behavior of the SC. Such fact also occurred with the remaining correlations between the different models, except between the $\Delta\dot{V}O_{2\,6\text{-}2}$ and the $\Delta\dot{V}O_{2\,6\text{-}3}$ ($r = 0.79$). In this case, there was a good correlation, suggesting that both analyses are presenting the same behavior of the SC.

There are important limitations in the use of mathematical models for the SC analysis which should be considered, especially when a steady state in the $\dot{V}O_2$ is not reached, for instance, in exercises characterized as very intense. In these cases, a plateau in the $\dot{V}O_2$ is not reached, what enables a totally accurate determination of the SC through the exponential adjustment. On the other hand, despite the SC determination through a pre-set interval be low reliable, since it does not consider the SC beginning, it has been suggested for the protocols of test which only performs one transition. In these cases there is a great biological variability between breaths ('noise'), which may make the process of interaction used by the mathematical models difficult. Further studies which search for improvement of the mathematical models are needed to minimize these limitations.

The origin of the kinetics SC of the $\dot{V}O_2$ is not completely defined yet. However, some evidence suggests that the SC behavior may be concerned with the processes which lead to fatigue. The study of the mechanisms which involve the SC may provide important information on the tolerance to exercise in healthy and with pathologies populations[26]. Within this context, the findings of the present study suggest that the use of different methodologies for the SC analysis (very intense domain) may generate distinct interpretations, and consequently may make the comparison of results among different studies difficult. Thus, more careful interpretation and comparison when different methodologies are used in the SC analysis are necessary in future investigations.

In conclusion, the data of the present study suggest that the SC magnitude during very intense exercise (75%Δ) may suffer influence of the method of analysis. The values of the SC obtained from the $\Delta\dot{V}O_{2\,6\text{-}2}$ and the $\Delta\dot{V}O_{2\,6\text{-}3}$ may be underestimated when compared to the values obtained by the bi-exponential adjustment models and with steady time of adjustment (120 s) of the 'primary component'. Moreover, the present study suggests that the SC determination during very intense exercise, as well as the comparison between the studies, should be carefully analyzed, since there may be differences of results when different methodologies of analyses are used.

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REFERENCES

1. Whipp BJ, Wasserman K. Oxygen uptake kinetics for various intensities of constant-load work. J Appl Physiol. 1972;33:351-6.
2. Barstow TJ, Mole PA. Linear and non-linear characteristics of oxygen uptake kinetics during heavy exercise. J Appl Physiol 1991;71:2099-106.
3. Özyener F, Rossiter HB, Ward HB, Whipp BJ. Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. J Physiol 2001;15:891-902.
4. Whipp BJ, Özyener F. The kinetics of exertion O_2 uptake: assumptions and inferences. Med Sport. 1998;51:39-49.
5. Neder JA, Nery LE. Fisiologia clínica do exercício – Teoria e prática. São Paulo: Editora Artes Médicas, 2003.
6. Barstow TJ, Jones AM, Nguyen PH, Casaburi R. Influence of muscle fiber type and pedal frequency on oxygen uptake kinetics of heavy exercise. J Appl Physiol. 1996;81:1642-50.
7. Koga S, Shiojiri T, Kondo N, Barstow TJ. Effect of increased muscle temperature on oxygen uptake kinetics during exercise. J Appl Physiol. 1997;83:1333-8.
8. Billat VL, Richard R, Binsse VM, Koralsztein, Haouzy P. The $\dot{V}O_2$ slow component for severe exercise depends on type of exercise and is not correlated with time to fatigue. J Appl Physiol. 1998;85:2118-24.
9. Jones AM, McConnell AM. Effect of exercise modality on oxygen uptake kinetics during heavy exercise. Eur J Appl Physiol. 1999;80:213-9.
10. Garland SW, Newham DJ, Turner DL. The amplitude of the slow component of oxygen uptake is related to muscle contractile properties. Eur J Appl Physiol. 2004;91;192-8.
11. Koppo K, Bouckaert J. The effect of prior high-intensity cycling exercise on the kinetics during high-intensity cycling exercise is situated at the additional slow component. Int J Sports Med. 2001;22:21-6.
12. Koppo K, Bouckaert J. The decrease in the $\dot{V}O_2$ slow component induced by prior exercise does not affect the time to exhaustion. Int J Sports Med. 2002;23:262-7.
13. Bearden SE, Moffatt RJ. $\dot{V}O_2$ slow component: to model or not model? Med Sci Sports Exerc. 2001;33:677-80.
14. Burnley M, Doust JH, Jones AM. Time required for the restoration of normal heavy exercise $\dot{V}O_2$ kinetics following prior heavy exercise J Appl Physiol. 2006; 101:320-7.
15. Rossiter HB, Ward SA, Kowalchuk JM, Howe FA, Griffiths JR, Whipp BJ. Effects of prior exercise on oxygen uptake and phosphocreatine kinetics during high-intensity knee-extension exercise in humans. J Physiol. 2001;15:291-303.
16. Caputo F, Denadai BS. Effects of aerobic endurance training status and specificity on oxygen uptake kinetics during maximal exercise. Eur J Appl Physiol. 2004; 93:87-95.
17. Beaver WL, Wasserman K, Whipp BJ. Improved detection of lactate threshold during exercise using a log-log transformation. J Appl Physiol. 1985;59:1936-40.
18. Taylor HL, Buskirk E, Henschel A. Maximal oxygen intake as an objective measure of cardiorespiratory performance. J Appl Physiol. 1955;8:73-80.
19. Lamarra N, Whipp BJ, Ward SA, Wasserman K. Effect of interbreath fluctuations on characterizing exercise gas exchange kinetics. J Appl Physiol. 1987;83:1318-25.
20. Barstow TJ, Casaburi R, Wasserman K. O_2 uptake kinetics and the O_2 deficit as related to exercise intensity and blood lactate. J Appl Physiol. 1993;75:755-62.
21. Carter H, Jones AM, Barstow TJ, Burnley M, Williams C, Doust JH. Oxygen uptake kinetics in treadmill running and cycle ergometry: a comparison. J Appl Physiol. 2000;89:899-907.
22. Carter H, Pringe JS, Jones AM, Doust JH. Oxygen uptake kinetics during treadmill running across exercise intensity domains. Eur J Appl Physiol. 2002;86:347-54.
25. Wilkerson DP, Koppo K, Barstow TJ, Jones AM. Effect of work rate on the functional 'gain' of phase II pulmonary O_2 uptake response to exercise. Respir Physiol Neurobiol. 2004;142:211-23.
26. Jones AM, Poole DC. Oxygen uptake dynamics: from muscle to mouth – An introduction to the symposium. Med Sci Sports Exerc. 2005;37:1542-50.