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Comparison of modelling techniques used to characterize moderate and heavy phase two recovery $\dot{V}O_2$ kinetics in young men

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RESUMEN

El análisis de la segunda fase de la captación pulmonar de oxígeno de la respuesta transitoria de recuperación del ejercicio (off-$\Phi 2\ \dot{V}O_2$) moderado (Mod) e intenso (Hvy) se evaluó en voluntarios jóvenes (n = 8, media ± DE: 25 ± 2 años). Completaron una prueba inicial tipo rampa (25 $W \bullet min^{-1}$) hasta el agotamiento, se identificaron el umbral ventilatorio ($\dot{V}_E T$) y las intensidades correspondientes a 80% $\dot{V}_E T$ (ModRel) y 120% $\dot{V}_E T$ (HvyRel) del ($Ejerc_{icio}Subm\acute{a}x_{imo}$). Además se seleccionó una intensidad absoluta de 50 W de ejercicio (ModAbs). Las transiciones off de cada ejercicio iniciaron con una línea de base de 1 min de ejercicio final (BSL) sin previo aviso al sujeto. Cada transición duró 6 min (6minRecEjerc) y fueron cuatro a seis para cada intensidad. La $\dot{V}O_2$ se midió de respiración a respiración en cada transición. Los datos fueron filtrados, interpolados a intervalos de 1-s y su ensamblado-promedio dio un perfil de respuesta única para cada sujeto e intensidad. Ésta se ajustó con modelos exponenciales de uno (1C), dos (2C) y tres componentes (3C) de diferentes ventanas de ajuste (→) y las estimaciones de sus parámetros como la constante de tiempo (τ) para cada componente. El mejor modelo de ajuste se identificó con la prueba de Fisher y/o el significado fisiológico del parámetro. ModAbs fue cinéticamente bien descrito por $2C,7P_{BSL \rightarrow 6minRecoveryExercise}$ aislando off $\Phi_2\ \dot{V}O_2$ ($\tau\Phi_2\ \dot{V}O_2 = 25 \pm 8$ s) o por $1C,4P_{0.3333\ min \rightarrow 6minRecEjerc}$ (omitiendo $\Phi 1 \dot{V}O_2$) semi-aislando off$\Phi_2 \dot{V}O_2$ ($\tau 2 = 28 \pm 4$ s). $2C,7P_{0.3333\ min \rightarrow 6minRecEjerc}$ semi-aislo cinéticamente off $\Phi_2\ \dot{V}O_2$ en ModRel ($\tau 2 = 22.5 \pm 4.2$ s) o en HvyRel ($\tau 2 = 22.8 \pm 6$ s) ($\tau_{2off\ (omitiendo\ \Phi_1\ \dot{V}O_2)\ EjercSubmax} = 24.42 \pm 5.30$ s. Estos modelos de mejor ajuste aislaron la off $\tau\Phi_2\ \dot{V}O_2$ del EjercSubmax en hombres jóvenes.

Palabras clave: *Hombres jóvenes, cinética de absorción de O_2, fase dos de O_2 de recuperación, modelos exponenciales, constante de tiempo.*

ABSTRACT

The analysis of the phase two pulmonary O_2 uptake ($\Phi_2\ \dot{V}O_2$) off-transient response during moderate (Mod)- and heavy(Hvy)-intensity constant-load post-exercise recovery was assessed, in young healthy male volunteers (n = 8; mean ± SD: 25 ± 2 yrs). Subjects completed an initial incremental ramp test (25 $W \bullet min^{-1}$) to volitional fatigue from which the ventilatory threshold ($\dot{V}_E T$) and work rates corresponding to 80%$\dot{V}_E T$ (ModRel) and 120%$\dot{V}_E T$ (HvyRel) ($Submax_{imal}Exerc_{ise}$) were identified. Also, it was selected an absolute work rate of 50 W (ModAbs). Off step-transitions in work rate were initiated from a baseline of 1 min (BSL) end exercise intensity without warning to the subject. Each off transition lasted 6 min (6minRecExerc) and 4-6 transitions were performed at each intensity. The $\dot{V}O_2$ response was measured breath-by-breath at baseline and throughout each transition. Data were filtered, interpolated to 1-s intervals and ensemble-averaged to yield a single response profile for each subject and intensity. The averaged response for each subject was fit with a one- (1C), two- (2C), and three-component (3C) exponential model by using different fitting windows (→), and parameter estimates BSL, time delay (TD), time constant (τ), amplitude (AMP) were determined for each component. Best fitting model was identified based on the Fisher's test and/or parameter's physiological meaning. ModAbs was well described by either $2C,7P_{BSL \rightarrow 6minRecExerc}$ kinetically isolateting off $\Phi_2\ \dot{V}O_2$ ($\tau\Phi_2\ \dot{V}O_2 = 25 \pm 8$ s) or $1C,4P_{0.3333\ min \rightarrow 6minRecExerc}$ (omitting $\Phi 1\ \dot{V}O_2$) kinetically semi-isolated off$\Phi_2\ \dot{V}O_2$ ($\tau 2 = 28 \pm 4$ s). The $2C,7P_{0.3333\ min \rightarrow 6minRecExerc}$ kinetically semi-isolated off $\Phi_2\ \dot{V}O_2$ for either ModRel ($\tau 2 = 22.5 \pm 4.2$ s) or HvyRel ($\tau 2 = 22.8 \pm 6$ s) ($\tau 2_{off\ (omitting\ f1\ O2)\ SubmaxExerc} = 24.42 \pm 5.30$ s.These best-fit models were those that well-described $\tau_2\ \dot{V}O_2$ off-transient kinetics (τ2) for submaximal exercise in young men.

Key words: *Young men, O_2 uptake kinetics, off-phase two O_2, exponential models, time constant.*

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INTRODUCTION

During the transition from exercise to recovery (off-transient response) the muscles' energy demands drop towards the resting levels but pulmonary oxygen uptake recovery ($\dot{V}O_2$ off-transient response) takes several minutes depending of the intensity of the exercise, which suggests that $\dot{V}O_2$ off-transient response is multi-factorially regulated.[1] For example, muscle blood flow, coupled with arterial O_2 content, will dictate the dynamics of O_2 delivery for skeletal muscle and the $\dot{V}O_2$ transient response during the recovery period following cessation of exercise; however, during recovery from exercise the estimated blood flow kinetics is biphasic, showing an early rapid decrease in blood flow, and the overall kinetics of blood flow is slow compared the estimated muscle oxygen uptake kinetics; in consequence, the entire kinetic characteristics of $\dot{V}O_2$ off-transient response during recovery from exercise remain in study, since the for moderate and heavy intensities of exercise the notion that the fundamental $\dot{V}O_2$ transient response kinetics are determined by an intramuscular mechanisms rather than by muscle perfusion *per se*.[1-3]

The recovery $\dot{V}O_2$ reflects the level of anaerobic metabolism in previous exercise and the respiratory, circulatory, hormonal, ionic, and thermal adjustments that exert influence during recovery.[2,3] Evermore, since the determinants of this $\dot{V}O_2$ off-transient response change with both time and intensity, it is not useful to consider exercise as a single state with respect to post-exercise recovery.[2] Actually, from an empirical $\dot{V}O_2$ off-transient response, at the cessation of the moderate exercise ($< \dot{V}_ET$, exercise intensity below ventilatory threshold), a rapid downward shift of $\dot{V}O_2$ off-transient response (off-phase one) generally occurs (off-Φ_1 $\dot{V}O_2$), followed by a decrease that is exponential in form (off-Φ_2 $\dot{V}O_2$) until either a new resting steady-state level is reached near to the original resting $\dot{V}O_2$ level ($< {}_ET$ off-Φ_3 $\dot{V}O_2$) for moderate exercise or a non new-resting steady-state for heavy intensity exercise ($> \dot{V}_ET$ off-Φ_3 $\dot{V}O_2$).[4] Throughout this off-Φ_3 respiratory feedback continues to fine tune the system until it returns to the resting homeostatic level. Either de Φ_2 $\dot{V}O_2$ on (during exercise)-, or off (during the post-exercise recovery)-transient response region has been demonstrated to be related to the arrival at the lung of the venous effluent from the exercising muscle by many researchers and is therefore considered the relevant region for comparison among different conditions.[1-4]

The $\dot{V}O_2$ off-transient response to $< \dot{V}_ET$ has been characterised with a first-order, three component exponential model incorporating a single time constant (τ), delay (TD or component) and amplitude (A).[5 6] Nevertheless, for heavy exercise ($> \dot{V}_ET$) the $\dot{V}O_2$ off-transient dynamics is more complex and require a second-order model,[6 7] for appropriate characterisation as a result of a slow kinetic component which is of delayed onset.[8] The response $> \dot{V}_ET$becomes more complex with an early component that typically projects to a value that has a gain similar to that of the $> \dot{V}_ET$ response, but which is supplemented by the addition of a delayed slow kinetic component. Nevertheless, the $\dot{V}O_2$ off-transient kinetics (mass rate of change in terms of τ) have not been assessed for the best mathematical model or models to characterise the $\dot{V}O_2$ ff-transient responses to exercise intensity $< \dot{V}_ET$ and $> \dot{V}_ET$ in the search for mechanisms determinants of this $\dot{V}O_2$ kinetic response. For simplicity we decided to assess in this study the fundamental Φ_2 $\dot{V}O_2$ off-transient kinetic (Φ_2 $\dot{V}O_2$ τ) response to exercise intensity $< \dot{V}_ET$ and $> \dot{V}_ET$ in young men.

We specifically addressed the questions:

- Which exponential mathematical model fitted best the $\Phi_2\dot{V}O_2$ into the entire $\dot{V}O_2$ off-transient response to submaximal exercise?
- Are the phase two $\dot{V}O_2$ time constant values, from the best fitting models, different to each other?

Hypothesis

If the exponential Φ_2 $\dot{V}O_2$ off-transient response to forcing functions of submaximal exercise is similarly modelled by different fitting models (monoexponential function, one component, two component and three component models) in terms of time constant duration, thus Φ_2 $\dot{V}O_2\tau$ estimated values should not be significantly different to each other, in young men.

MATERIAL AND METHODS

Subjects

Eight young healthy male adults participated in this study. The University's Review Board for Research Using Human subjects approved this research. Subjects gave their informed consent after the experimental protocol and possible risks were explained to each participant. Subjects were scheduled for cycle ergometer testing sessions in an air conditioned laboratory (19 to 22 ºC). Subjects were studied on 4 to 6 occasions with each visit separated by at least 2 days.

Ramp test. Cycle ergometer

After the researcher manually set cycle ergometer loads of 25 W, 100 W and 300 W, the system calculated, by linear regression, slope and intercept (load coefficient). On the initial visit to the laboratory each subject performed and incremental exercise test, in which after initiated at 60 rpm by 4 min "loadless" (actual constant power output ≈ 15 W) pedalling, the power output increased as a ramp function at 25 W•min^{-1} to volitional fatigue for the determination of the $\dot{V}_ET$, peak O_2 uptake ($\dot{V}O_2$peak), heart rate peak and maximal work rate. Subjects exercised in the upright position on an electrically-braqued cycle ergometer (Lode, Model H-300-R) and the resistance on the cycle ergometer was computer-controlled to produce a ramp signal that correspond to a linear increase in power output. The $\dot{V}O_2$ averaged over the final 15 s of the incremental test prior to fatigue was taken as $\dot{V}O_2$peak.

The estimated lactate threshold ($\dot{V}_ET$), a non-invasive method expressed as a percentage of the $\dot{V}O_2$max, was defined as Davis, *et al.*[9] according to Whipp, *et al.*[10] and Beaver, *et al.*[11,12] The $\dot{V}O_2$ at $\dot{V}_ET$ was determined by two independent investigators as Davis, *et al.*[9] The two independent observers made the $\dot{V}_ET$ determination with good interobserver agreement (r = 0.9397). $\dot{V}O_2$ corresponding to the time of the $\dot{V}_ET$ was calculated as Wasserman, *et al.*[13]; as well as, the work rate corresponding to the $\dot{V}O_2$ at 80% $\dot{V}_ET$ and 120% $\dot{V}_ET$ was calculated.[14]

Submaximal constant-loadless leg cycling exercise tests

Tests to determine $\dot{V}O_2$ off-transient kinetics were performed during subsequent visits to the laboratory. Subjects performed constant-load leg cycling exercise where the power output increased as a step function from "loadless" cycling to a power output corresponding to moderate or heavy-intensity exercise.[2] Three different intensities of exercise were studied and consisted in square waves of 50 W (ModAbs, absolute power output of moderate-intensity), power outputs corresponding to 80% $\dot{V}_ET$ (ModRel, relative power output of moderate-intensity) and 120% $\dot{V}_ET$ (HvyRel, relative power output of heavy-intensity), with each subject performing all three exercise intensities during the curse of the study. Each subject pedalled at 60 rpm. The protocol began with a base line off 1 min end exercise (BSL) load-cycling, followed by a step decrease in power output back to loadless cycling lasting 6 min in duration (off-transition, recovery of exercise). Changes in power output were initiated without warning the subject. In order to reduce variability associated with biological testing and to improve the signal-to-noise ratio for data each subject performed 4-6 transitions for the 50 W and 80% $\dot{V}_ET$ protocols, and 2 to 4 repetitions for the 120% $\dot{V}_ET$ protocol. Approximately 3 transitions were performed on each visit with the protocols assigned in the order: 50 W (< $\dot{V}_ET$), 80% $\dot{V}_ET$ (< $\dot{V}_ET$), and 120% $\dot{V}_ET$ (> $\dot{V}_ET$).[14]

Ventilation and pulmonary gas exchange

A calibration module menu allowed the routine running of any of the separate calibrations. The bi-directional turbine and volume transducer (Ventilation Measurement Module-110, Alpha Technologies) that produced the signal proportionally to the flows, measured inspired and expired airflow and ventilatory volumes; the volume was calibrated daily using a syringe of known volume (3.01 L) and for flow corrections, the turbine flow values were calibrated by this known volume of gas passing through the turbine ten times in each direction. After a correction factor calculated for both inspired and expired volumes, the inspired and expired gases were sampled continuously (1 mL•s^{-1}) at the mouth and analysed for fractional concentrations of O_2, CO_2, and N_2 using a respiratory mass spectrometer (Perkin Elmer MGA-1100 or Airspec MGA2000) previously calibrated with precision-analysed gas mixtures with air (pO_2 = 20.93%, pCO_2 = 0.03%, and N_2 = 78.1%) and gas mixtures of known concentrations (pO_2 = 9.13%, pCO_2 = 7.02%, and N_2 = 83.85%) *vs.* sampled readings, the slope and intercept were displayed as linear regression (gas coefficient).[14] Analog (electrical) signals from the mass spectrometer and turbine transducer were sampled and digitized every 20 ms and stored on computer for later analysis. Gas concentration signals were aligned with inspired and expired gas volumes after correcting for the time delay of the analysis system. Ventilation, $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated with the corrections made for breath-by-breath fluctuations in lung gas stores.[11,14] These data were stored in a microcomputer and further corrected for changes in lung gas stores to yield estimates of alveolar gas exchange to be interpolated second by second.[11] These data were summed mathematically (integration by the trapezoidal method of summation) and then reported either per breath-by-breath or per unit time by an analog integrator (or analog-to-digital converter) and digital computer. The breath by breath gas exchange data collected for this study were expired ventilation ($\dot{V}_E$), $\dot{V}CO_2$ and $\dot{V}O_2$. The alveolar $\dot{V}O_2$ data were filtered to remove breaths deviating by more than 20%, to increase the resolution at the onset of the exercise, from a five breath moving average.[14] Temperature and water vapour corrections were based on conditions measured near the mouth.

During each test, subjects breathed through a low_resistance mouthpiece connected to a turbine, with the nose occluded by a noseclip. Subjects pedalled while breathing. Ventilation and gas exchange ($\dot{V}O_2$, $\dot{V}CO_2$) were calculated breath-by-breath by a computer based programme. Inspired and expired flow rates were measured using a low dead space (90 mL) bidirectional turbine. The flow and gas concentrations were aligned by calibration of the time delay for gas transport and analysis by the mass spectrometer (approximately 250 ms). Changes in gas concentrations were aligned with the inspired and expired gas volumes by measuring the time delay for a square wave bolus of gas passing the turbine to the resulting changes in fractional gas concentrations as measured by the mass spectrometer. All the input signals were received via analog_to_digital board, and the output signals to control the various pieces of exercise equipment were transmitted via digital_to_analog board. Data were stored on a hard disc system for later analyses.

Data analysis

The breath by breath 50 W, 80% $\dot{V}_ET$, and 120% $\dot{V}_ET$ data were interpolated to 1 s interval, and each repetition was time aligned and assemble averaged to provide a single response for each subject. The single response (50 W, 80% $\dot{V}_ET$, 120% $\dot{V}_ET$ overlayed data) was used for determining the kinetics of the $\dot{V}O_2$ off-transient response to submaximal exercise. The end $\dot{V}O_2$ post-exercise recovery was taken as the mean $\dot{V}O_2$ during the last 0.25 min post-exercise recovery. We calculated also the slope subthreshold $\dot{V}O_2$-power relationship and the $\dot{V}O_2$ during loadless pedalling cycling.

Table 1. Seven different exponential mathematical fitting models used to assess the $\dot{V}O_2$ off-transient response during submaximal exercise in young adult men.

Model number	Fitting Model	Temporal Parameter									
		1	2	3	4	5	6	7	8	9	10
		$A_{mplitud}0$	A1 (mLO_2 min-1)	A2	A3	$T_{ime}D_{elay}1$	TD2	TD3 (s)	τ1	τ2	τ3
1	1C,4P$_{arameters}$ 0.3333 min to 6 min*	[Virtual BSL]	-	✓	-	-	✓	-	-	✓	-
2	1C,3P BSL1 min to 6 min	✓	✓	-	-	-	-	-	✓	-	-
3	1C,4P BSL1 min to 6 min	✓	✓	-	-	✓	-	-	✓	-	-
4	2C,7P BSL1 min to 3 min	✓	✓	✓	-	✓	✓	-	✓	✓	-
5	2C,7P 0.3333 min to 6 min	[Virtual BSL]	-	✓	✓	-	✓	✓	-	✓	✓
6	2C,7P BSL1 min to 6 min	✓	✓	✓	-	✓	✓	-	✓	✓	-
7	3C,10P BSL1 min to 6 min	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

–: No estimated temporal parameter. *Fitting (period of time) window. BL1: one min end exercise baseline. 0 3333: 20 s after BL1. 6min: Six min end recovery exercise. 1, 2, and 3 in A, TD, and τ (time constant) refer to the phases one, two, and three, respectively, in $\dot{V}O_2$ off-transient response during submaximal exercise. 1C, 2C, and 3C: One component (one TD), Two components two TDs), and Three components (three TDs) models. 1C,3P mono-exponential function): $\dot{V}O_2(\tau) = A_0 + A1 \bullet (1\text{-}e^{-(t/\tau 1)})$; 1C,4P: $O_2(t) = A_0 + A1 \bullet (1\text{-}e^{-[(t-TD1)/\tau 1]})$. 2C,7P: $\dot{V}O_2(t) = A_0 + A1 \bullet (1\text{-}e^{-[(t-TD1)/\tau 1]}) + A2 \bullet (1\text{-}e^{-[(t-T2)/\tau 2]})$. 3C,10P: $\dot{V}O_2(t) = A_0 + A1 \bullet (1\text{-}e^{-[(t-TD1)/\tau 1]}) + A2 \bullet (1\text{-}e^{-[(t-T2)/\tau 2]}) + + A3 \bullet (1\text{-}e^{-[(t-T3)/\tau 3]})$. $\dot{V}O_2$(t): Mass rate of change per unit of time ($d\dot{V}O_2 \bullet dt^{-1}$) assuming TD = 0.. a_0: Baseline; a is the $\dot{V}O_2$ distance value from a_0 to the $\dot{V}O_2$ recovery required, or recovery steady-state i.e., the difference between the end exercise baseline and the unloaded pedalling recovery-exercise $\dot{V}O_2$ response). $1\text{-}e^{-(t/\tau)}$: the negative exponential distribution (Evans, Hasting and Peacock, 1993). $e^{-(t/\tau)}$: the die-away factor with the time constant t, for an exponential decrease (off-transient $\dot{V}O_2$ response). t: time in which the transient $\dot{V}O_2$ response is gradually (exponentially) dying away; when t = t means the time required for the transient $\dot{V}O_2$ response to die away to e^{-1} part (e^{-1} = 1/2.71828 = 0 3678) of its original value, thus, τ = 1-0.3678 = 0.63, and e = 2.718281 = $[(1 + n^{-1})]^n$, n ≥ 10 and 'e' is incommensurable with 1.

Modelling

The $\dot{V}O_2$ off-transient response $< \dot{V}_ET$ and $> \dot{V}_ET$ exercise intensities was modelled by using the one component (1C), two component (2C) and three component (3C) exponential mathematical expressions with seven fitting models (Table 1) previously published.[3-8,14] These seven fitting models using the fitted period of time (fitting window) from either 20 s (0.3333 min) or one min baseline (BL1) after the offset of the exercise (end of the ergometric exercise) to (→) either 3 min off-transient $\dot{V}O_2$ response or 6 min end-ergometric exercise (end post-exercise recovery) were the $1C,4P_{0.3333 \rightarrow 6\,min}$ and $2C,7P_{0.3333 \rightarrow 6\,min}$ (Table 1); $2C,7P_{BL1 \rightarrow 3\,min}$ (Table 1); $1C,3P_{BL1 \rightarrow 6\,min}$, $1C,4P_{BL1 \rightarrow 6\,min}$, $2C,7P_{BL1 \rightarrow 6\,min}$ and $3C,10P_{BL1 \rightarrow 6\,min}$ (Table 1), to estimate off $\tau\ \Phi_2\ \dot{V}O_2$. The fitting models two and four were used to assess the best fit compared to multiple component models six and seven (Table 1). The multi-component models five (omitting phase one), six and seven (except for absolute moderate-intensity post-exercise recovery) that fitted data from the offset towards the recovery of exercise steady-state of the submaximal exercise that included BSL (Table 1) were used to assess the best physiological (Φ_{2_Phys}) and ($\Phi_{2\_PhysStat}$) and/or statistical (Φ_{2_Stat}) fit of $\Phi_2\ \dot{V}O_2$ off-transient (post-exercise recovery) response from submaximal exercise. The kinetic analysis of $\Phi_2\ \dot{V}O_2$ was assessed in terms of the time constant two (off-$\tau\ \Phi_2$).

Estimates of the parameters of the response, specifically the $\Phi_2\ \dot{V}O_2\ \tau$ was compared together with a statistical analysis of how well each model fitted the $\dot{V}O_2$. We specifically addressed:

- The effect of incorporating the analysis of $\Phi_1\ \dot{V}O_2$ data withing a model to physiologically isolate Φ_2, and
- The effect of incorporating the analysis of $\Phi_3\ \dot{V}O_2$ data within a model to physiologically isolate Φ_2 and to statistically isolate Φ_2, and
- Differences between fitting entire $\dot{V}O_2$ off-transient response *vs*. a fitting non-entire (omitting off $\Phi_1\ \dot{V}O_2$) window for $\Phi_2\ \dot{V}O_2$ off-transient data. The acceptability of the fitting models were also assessed primarily on whether the information provided by the models was consistent with current understanding of the $\dot{V}O_2$ off-transient response (Phys); as well as, statistical (Stat) merits.

Statistical analyses

The goodness of fit by each fitting model was assessed using the lowest residual sum of squares (RSS values) from a computerized nonlinear regression technique.[14] The best statistical fit exponential mathematical model (Stat) was assessed using the RSS values (the explained deviations from the nonlinear mean square) for models that fit the same number of experimental data points or the mean square error (MSE values, the deviations within- models mean square) for models which fit a different number of experimental data points by performing a Fisher's test (F_{value}, at 0.05 level of significance and one tailed) described previously.[15,16] The number of permutations (nP'x) for model comparisons was calculated as a factorial function according to Zar.[14,16] For example, in this study we compared seven different fitting models (Table 1) previous published, then (7!/((7-2)!*2) we performed 21 permutations. Data treatment consisted of group analyses performed using either a One Way Analysis of Variance (ANOVA; Student-Newman-Keuls and Tukey *post-hoc* analyses) or Kruskal-Wallis ANOVA on Ranks procedure Dunns' Method (when variances of the dependent variable were unequal or the distribution of the dependent variable was not normal), to compare kinetic temporal parameters from the exercise square waves.[16] The probability level denoted significance at $P \leq 0.05$.

RESULTS

Physical characteristics and ramp exercise test

The subject characteristics, maximal power output, $\dot{V}O_2$ pick, and $\dot{V}_ET$ values are presented in table 2. The end-exercise $\dot{V}O_2$, exercise intensity expressed as absolute power output and relative to the $\dot{V}_ET$ (%$\dot{V}_ET$) are presented in table 2. Both the power output significantly lasted-, and the square wave test end-exercise $\dot{V}O_2$- significantly lasted- {50W < 80%$_E$T < 120%$_E$T} different to $\dot{V}O_2\ \dot{V}_ET$ (Table 2). The $\dot{V}O_2$ relative exercise intensity the $\dot{V}_ET$ (%$\dot{V}_ET$) lasted: 50 W < 80% $\dot{V}_ET$ < 120% $\dot{V}_ET$ (Table 2). The W relative exercise intensity the $\dot{V}_ET$, calculated as $W_{\_intensity\ exercise}/W_{\dot{V}ET}$, lasted (%, mean ± SD) lasted: $42 \pm 7_{\_50\,W} < 68 \pm 3_{\_80\%\dot{V}ET} < 130 \pm 5_{\_120\%\dot{V}ET}$ ($F_{ratio} = 28$, $P < 0.0002$).

O_2 linear regression

Since $\dot{V}O_2/W_{\_50\,W}$ was not significantly different to $\dot{V}O_2/W_{\_80\%\dot{V}ET}$; then moderate intensity exercise slope (coefficient) of the subthreshold $\dot{V}O_2$-power output relationship and the $\dot{V}O_2$ during off (loadless) cycling (end post-exercise recovery) were: $\dot{V}O_2/W = 12.9 \pm 1.1$ mL•min^{-1}•W^{-1} (n = 16, r = 0.97, P < 0.001); $\dot{V}O_{2}$_off loadless = 732.7 ± 77.7 mL•min^{-1}.

Table 2. Subject characteristics and data for maximal and submaximal exercise in eight young adult men.

Age	Height	Mass	Work Rate Max	O_2 peak	$_E$T		
(years)	(cm)	(kg)	(Watts)	($l \cdot min^{-1}$)	($ml \cdot kg^{-1} \cdot min^{-1}$)	($ml \cdot min^{-1}$)	(% $\dot{V}O_2$peak)
25 ± 2	180 ± 4	79 ± 8	250 ± 42	3.7 ± 0.5	47.5 ± 5.0	1920 ± 189	52 ± 4

50 W[A]	Moderate intensity exercise				Heavy intensity exercise							
$\dot{V}O_2$ ($ml \cdot min^{-1}$)	% $\dot{V}_E$T	% $\dot{V}O_2$peak	PO (W)	$\dot{V}O_2$ ($ml \cdot min^{-1}$)	% $\dot{V}_E$T	% $\dot{V}O_2$peak	PO (W)	$\dot{V}O_2$ ($ml \cdot min^{-1}$)	% $\dot{V}_E$T	% $\dot{V}O_2$peak	$\dot{V}_E$T	(w)
1182[a]	62[c]	32	84[b]	1632[a]	85[c]	44	160[b]	2716[a]	143[c]	75	124[b]	
± 87	± 7	± 4	± 14	± 213	± 5	± 4	± 23	± 380	± 11	± 10	± 20	

All data are mean ± SD. A: Absolute PO. $\dot{V}_E$T: Estimated lactate threshold. PO: Power output. % $\dot{V}_E$T calculated as ($\dot{V}O_2$ exercise intensity) / $\dot{V}O_2$ $\dot{V}_E$T) • 100. % $\dot{V}O_2$peak calculated as ($\dot{V}O_2$ exercise intensity) / $\dot{V}O_2$peak) • 100. Significant differences between means with the same letter, allocated by ANOVA procedure: Student Newman-Keuls test: $^aF_{ratio}$ = 6, P < 0.001 (included differences from mean $\dot{V}O_2 \dot{V}_E$T = 1918 ± 189[a], $ml \cdot min^{-1}$); $^bF_{ratio}$ = 8, P < 0.001; $^cF_{ratio}$ = 30, P < 0.001.

Mathematical modelling

The $\dot{V}O_2$ off-transient time course for absolute (50 W), relative moderate (80% $\dot{V}_E$T), and relative heavy (120% $\dot{V}_E$T) square-wave exercise tests from our eight subjects sample are presented in figure 1. The off-transient $\dot{V}O_2$ response to submaximal exercise, constant off-loadless cycling was analysed with seven exponential mathematical fitting models (Table 1) previously published. The residual sum of squares and mean square error estimates for kinetic analysis of $\dot{V}O_2$ during the off-transient post-exercise recovery for submaximal exercise as estimated by those seven different exponential mathematical models (Table 1) are presented in table 3. The two out mathematical model permutation comparisons for the off-transient $\dot{V}O_2$ submaximal exercise are presented in table 3. The amplitude and the parameter estimates determined from kinetic analy f $\dot{V}O_2$ during the off-transient of steady-state exercise, as estimated by the best fitting models from these study, are presented in table 4 for absolute-, 80% relative-, and 120% relative-work rate. The best final exponential mathematical fitting models that characterised the Φ_2 off-transient $\dot{V}O_2$ kinetics (τ_2) during submaximal exercise, from this study, are shown in table 5.

Absolute moderate intensity (ModAbs) exercise

$\dot{V}O_2$ off-transient response to ModAbs (50W) exercise was Stat (P < 0.05) best fitted by model A (1C,4P$_{0.3333\,min \rightarrow 6\,min}$) compared models B, C, D, and F (Table 3); model B did also compared models C and D (Table 3) but model B (like model C) has no Phys sense because it did not distinguish more than one transient phase of response. Thus, model F (2C,7P$_{BSL\,1\,min \rightarrow 6\,min}$) was both Stat (P < 0.05) and Phys (distinguished two transient phases of response) best compared model B (Table 3) on fitting the $\dot{V}O_2$ off-transient response to ModAbs exercise. Model D (2C,7P$_{BSL\,1\,min}$ → 3 min) was Stat (P < 0.05) superior but not Phys compared model F, because model D did not distinguish the end Φ_2 and the start of the steady-state $\dot{V}O_2$ off-exercise for ModAbs (Table 3) besides Φ_1 is frequently extremely difficult to fit. Evermore, models A and F fitted Stat same $\dot{V}O_2$ off-transient response to ModAbs (Table 3) their residuals fluctuated pretty much the same around zero (Figure 2), their off Φ_2 $\dot{V}O_2$ amplitudes were similar (Table 4), their off Φ_2 ΦO_2 TD resulted significantly (P < 0.05) different (Table 4) and their off Φ_2 $\dot{V}O_2$ kinetics (τ2) were similar to each other (Table 4). In consequence, on one hand the model Φ (2C,7P$_{BSL\,1\,min}$ →6 min) was the best both Stat and Phys on isolating off Φ_2 $\dot{V}O_2$ and its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$)

Table 3. Residual sum of squares and mean square error estimates for kinetic analysis of $\dot{V}O_2$ during the off-transient of recovery steady-state submaximal exercise as estimated by seven different exponential mathematical models and their 21 two out mathematical model permutations in eight young adult men.

		Exercise intensity				
	Moderate (50 Watts)		Moderate (80% $\dot{V}_ET$)		Heavy (120% $\dot{V}_ET$)	
Fitting model	RSS (x10^5)	MSE	RSS (x10^5)	MSE	RSS (x10^5)	MSE
A $1C,4P_{0.3333\ min \rightarrow 3\ min}$	3.68 ± 1.67	1095 ± 498	5.69 ± 3.08	1702 ± 927	26.07 ± 34.05	7825 ± 10112
B $1C,3P_{BSL1\ min \rightarrow 6\ min}$	5.29 ± 2.08	1243 ± 457	4.06 ± 1.43	2160 ± 980	44.54 ± 53.75	10799 ± 12887
C $1C,4P_{BSL1\ min \rightarrow 6\ min}$	4.64 ± 1.82	1121 ± 438	7.95 ± 3.62	1904 ± 872	40.54 ± 50.64	9829 ± 12145
D $2C,7P_{BSL1\ min \rightarrow 3\ min}$	2.25 ± 0.88	963 ± 379	4.08 ± 1.63	1750 ± 697	22.91 ± 32.34	9830 ± 13879
E $2C,7P_{0.3333\ min \rightarrow 6\ min}$	-	-	5.43 ± 2.67	1639 ± 812	23.86 ± 30.9	7173 ± 9303
F $2C,7P_{BSL1\ min \rightarrow 6\ min}$	4.51 ± 1.82	1091 ± 456	21.63 ± 31.73	2000 ± 978	35.18 ± 48.20	8579 ± 11648
G $3C,10P_{BSL1\ min \rightarrow 6\ min}$	-	-	13.14 ± 3.85	3197 ± 937	28.46 ± 37.74	3694 ± 2106

FittingModel		Moderate (50 Watts)		Moderate (80% $\dot{V}_ET$)		Heavy (120% $\dot{V}_ET$)	
Simple *vs.* Complex		F_{value}Calculated[b]					
No[a]		F_{RSS}	F_{MSE}	F_{RSS}	F_{MSE}	F_{RSS}	F_{MSE}
1 $1C,4P_{0.3333\ min \rightarrow 6\ min}$ [A]	$1C,3P_{BSL1\ min \rightarrow 6\ min}$ [B]	-	7*,A	-	9.22*,A	-	11.34*,A
2 $1C,4P_{0.3333\ min \rightarrow 6\ min}$	$1C,4P_{BSL1\ min \rightarrow 6\ min}$ [C]	-	0.41,A	-	1.89*,C_{om}	-	3.63*,C_{om}
3 $1C,4P_{0.3333\ min \rightarrow 6\ min}$	$2C,7P_{BSL1\ min \rightarrow 3\ min}$ [D]	-	0.15,A	-	0.03,A	-	0.22,A
4 $1C,4P_{0.3333\ min \rightarrow 6\ min}$	$2C,7P_{0.3333\ min \rightarrow 6\ min}$ [E]	-	-	-	-	10.24*,C_{om}	-
5 $1C,4P_{0.3333\ min \rightarrow 6\ min}$	$2C,7P_{BSL1\ min \rightarrow 6\ min}$ [F]	-	0.08,A	-	3.10*,C_{om}	-	1.83*,C_{om}
6 $1C,4P_{0.3333\ min \rightarrow 6\ min}$	$3C,10P_{BSL1\ min \rightarrow 6\ min}$ [G]	-	-	-	0.0,A	-	27.95*,C_{om}
7 $1C,3P_{BSL1\ min \rightarrow 6\ min}$ [B]	$1C,4P_{BSL1\ min \rightarrow 6\ min}$	-	0.0,B	-	0.0,B	-	0.0,B
8 $1C,3P_{BSL1\ min \rightarrow 6\ min}$	$2C,7P_{BSL1\ min \rightarrow 3\ min}$	-	0.27,B	-	0.22,B	-	0.09,B
9 $1C,3P_{BSL1\ min \rightarrow 6\ min}$	$2C,7P_{0.3333\ min \rightarrow 6\ min}$	-	-	-	-	-	7.01*,C_{om}
10 $1C,3P_{BSL1\ min \rightarrow 6\ min}$	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	15.16*,C_{om}	-	51.65*,C_{om}	-	23.48*,C_{om}	-
11 $1C,3P_{BSL1\ min \rightarrow 6\ min}$	$3C,10P_{BSL1\ min \rightarrow 6\ min}$	-	-	-	0.0,B	28.26*,C_{om}	-
12 $1C,4P_{BSL1\ min \rightarrow 6\ min}$ [C]	$2C,7P_{BSL1\ min \rightarrow 3\ min}$	-	0.15,C	-	0.08,C	-	0.0,C
13 $1C,4P_{BSL1\ min \rightarrow 6\ min}$	$2C,7P_{0.3333\ min \rightarrow 6\ min}$	-	-	-	-	-	5.36*,C_{om}
14 $1C,4P_{BSL1\ min \rightarrow 6\ min}$	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	3.46*,C_{om}	-	74.42*,C_{om}	-	17.92*,C_{om}	-
15 $1C,4P_{BSL1\ min \rightarrow 6\ min}$	$3C,10P_{BSL1\ min \rightarrow 6\ min}$	-	-	-	0.0,C	24.77*,C_{om}	-
16 $2C,7P_{BSL1\ min \rightarrow 3\ min}$ [D]	$2C,7P_{0.3333\ min \rightarrow 6\ min}$	-	-	-	-	-	0.77,D
17 $2C,7P_{BSL1\ min \rightarrow 3\ min}$	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	-	0.23,D	-	0.25,D	-	0.29,D
18 $2C,7P_{BSL1\ min \rightarrow 3\ min}$	$3C,10P_{BSL1\ min \rightarrow 6\ min}$	-	-	-	0.0,D	-	3.28*,C_{om}
19 $2C,7P_{0.3333\ min \rightarrow 6\ min}$ [E]	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	-	-	-	-	-	2.89*,C_{om}
20 $2C,7P_{0.3333\ min \rightarrow 6\ min}$	$3C,10P_{BSL1\ min \rightarrow 6\ min}$	-	-	-	0.0E	-	19.39*,C_{om}
21 $2C,7P_{BSL1\ min \rightarrow 6\ min}$ [F]	$3C,10P_{BSL1\ min \rightarrow 6\ min}$	-	-	-	0.0,F	-	27.57*,C_{om}

All RSS and MSE data are mean ± SD. $\dot{V}_ET$: estimated lactate threshold. -: it did not apply. RSS: residual sum of squares (expressed as RSS x 10^5). MSE: mean square error. 1C, 2C, and 3C refer the one component, two components, and three components exponential mathematical models. 3P, 4P, 7P, and 10P refer the three, four, seven, and ten parameters respectively. A to G: seven fitting models as in table 1. a: the number of circular permutations (nP'x) for model comparisons (No.) was calculated according to Zar (1996); i.e., 7P'2= (7!)/((7-2)! 2)) = 21, permutations. b: the best statistical fit model was assessed using either the RSS values for models which fit the same number of experimental data points or the MSE values for models which fit a different number of experimental data points by performing a Fisher's test (F_{value}, at 0.05 level of significance and one tailed*: $F_{tabulated}$0.05 (1a) = 1.15) (Motulsky and Ransnas, 1987; Zar, 1996). If $F_{calculated} > F_{tabulated}$ then "complex" model fits best; contrary wise, if $F_{calculated} < F_{tabulated}$ then "simple" model fits best. BL1: One min baseline. 0.3333 min: the $\dot{V}O_2$ corresponding to 20 s after the end exercise with the recovery exercise transient. 3 min: Three min recovery exercise transient. 6 min: Six min recovery exercise transient. →: fitting (period of time) window.*

Table 4. Temporal parameters determined from the kinetic analyses of $\dot{V}O_2$ during the off-transient of recovery steady-state submaximal exercise as estimated by the best exponential mathematical fitting models in eight young adult men.

Work rate	Fitting Model (ml·min-1)	$B_{ase}L_{aine}$ (A0) (ml·min-1)	$A_{mplitude}\Phi_1$ (A1) (ml·min-1)	$A_{mplitude}\Phi_2$ (A2) (ml·min-1)	$A_{mplitude}\Phi_3$ (A3) (ml·min-1)	$A_{mplitude}$Total
50 Watts	$1C,4P_{0.3333\ min \rightarrow 6\ min}$	[1029.21 105.80]	- -	291.63[e g i] ±64.10	- -	- -
	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	1188.76[a] ±95.11	206.35[c] ±123.41	244.08[e g] ±109.81	- -	450.43[k] ±44.64
80 %$\dot{V}_ET$	$1C,4P_{0.3333\ min \rightarrow 6\ min}$	[1377.15 80.68]	- -	631.65[j] ±124.9	- -	- -
	$2C,7P_{0.3333\ min \rightarrow 6\ min}$	[1254.60 151.01]	- -	441.75[e] ±96.01	88.30 ±68.43	- -
	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	1629.86[a] ±230.56	413.64 ±229.02	472.81[e] ±189.97	- -	886.46 ±203.05
120 %$\dot{V}_ET$	$2C,7P_{0.3333\ min \rightarrow 6\ min}$	[2134.63 ±199.31]	- -	1152.08[h] ±174.91	135.93 ±8.39	- -
	$3C,10P_{BSL1\ min \rightarrow 6\ min}$	2783.10[b] ±458.57	612.63[d] ±244.45	1269.28[f] ±352.76	94.12 ±61.63	1976.02[l] ±460.53

Work rate	Fitting Model	Φ_1TD	Φ_2TD (s)	Φ_3TD (s)	$\Phi_1\tau$ (s)	$\Phi_2\tau$ (s)	$\Phi_3\tau$ (s)	MRT_{exp} (s)	RSS (s)	MSE (x 10^5)	Best Fit Type
50 Watts	$1C,4P_{0.3333\ min \rightarrow 6\ min}$	-	[0.100 -	- ± 2.80]	- -	28.00[o] -	- ± 3.99	- -	3.68 -	1095.14 ± 1.67	Stat Φ_2 Semi-isolated ± 498.12
	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	3.54	17.01 ± 3.65	- ± 5.08	16.65 -	25.07[o] ±8.94	- ± 8.37	35.03[s] -	4.51 ± 6.63	1091.12 ± 1.82	Stat & Phys Φ_2 isolated ± 456.80
80%$\dot{V}_ET$	$1C,4P_{0.3333\ min \rightarrow 6\ min}$	-	[-3.86 -	- ± 6.25]	- -	31.20 -	- ± 5.28	- -	5.69 -	1702.44 ± 3.08	 ± 927.54
	$2C,7P_{0.3333\ min \rightarrow 6\ min}$	-	[6.50 -	23.84[m] ± 3.43]	- ±3.19	22.47[o] -	161.54[q] ± 4.15	- ± 6.32	5.43 -	1639.37 ± 2.70	Stat Φ_2 Semi-isolated ± 812.38
	$2C,7P_{BSL1\ min \rightarrow 6\ min}$	3.86	[17.83 ± 4.69	- ± 5.30]	16.70 -	38.02[p] ±6.30	- ± 7.10	39.11 -	21.63 ± 7.70	2000.66 ± 31.73	 ± 979.00

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120%$\dot{V}_E$T	2C,7P$_{0.3333\ min \rightarrow 6\ min}$	-	[5.94	87.69^n	-	22.77^o	84.14^r	-	23.87	7173.75	Stat Φ_2 Semi_Isolated
			-	± 4.64]	±28.43	-	± 5.96	± 51.06	-	± 30.97	± 9303.32
	3C,10P$_{BSL1\ min \rightarrow 6\ min}$	-0.58	21.84	118.68^n	13.99	28.25^o	145.71	48.09^t	28.46	3694.50	Stat & "Phys" Φ_2 Isolated
			± 2.94	± 5.83	±5.99	±7.36	± 4.76	± 34.96	± 9.57	± 37.74	± 2106.59

All data are mean ± SD. $\dot{V}_E$T: estimated lactate threshold. -: it did not apply. Φ_1, Φ_2 and Φ_3: phases 1, 2 and 3 of the increase in $\dot{V}O_2$ during the off-transient of submaximal exercise. BSL: one min end exercise baseline. 6 min: six min recovery exercise. →: fitting (period of time) window. a_0: the baseline $\dot{V}O_2$ prior to the transition to recovery submaximal exercise. Models as in table 1. The a_0 shown in square brackets is the $\dot{V}O_2$ corresponding to 0.3333 min (20 s) after the end exercise with the recovery exercise transient, and thus represents a "virtual" baseline $\dot{V}O_2$. $A_{mplitude\ Total\ 2C\ model} = A_1 + A_2$; $A_{mplitude\ Total\ 3C\ model} = A_1 + A_2 + A_3$. Actual end-exercise (experimental baseline) $\dot{V}O_2$ ($mL{\bullet}min^{-1}$) were 1181 ± 88 for 50 Watts, 1,631 ± 212 for 80%ET and 2,715 ± 378 for 120%$\dot{V}_E$T, calculated as the mean $\dot{V}O_2$ using the final 15 s of constant load exercise. TD: time delay; τ: time constant. MRT_{exp}: exponential mean response time. RSS: residual sum of squares (expressed as RSS x 10^5). MSE: mean square error. The TD2 shown in square brackets represent a "virtual" TD2. Stat and Phys as in table 4. -: it did not apply. Significantly ($P < 0.005$) different, allocated by ANOVA procedure Kruskal-Wallis-Tukey's method, and also post hoc Holm-Sidak: a ≠ b (H ≠ 19.6), c ≠ d (F ≠ 7.7), e ≠ j (H = H = 46.4), k ≠ l (H = 35): m ≠ n (H = 18), o ≠ p (F = 7), q ≠ r (H = 10.2), s ≠ t (F = 27). TRM_{exp}: the time required to reach 63% of the total amplitude of response from the base line to its final value ($\dot{V}O_2$). $TRM_{exp}\_2C = [A_1/(A_1 + A_2)] \bullet (TD1 + \tau1) + [A_2/(A_1 + A_2)] \bullet (TD2 + \tau2)$, $TRM_{exp}\_3C = [A_1/(A_1 + A_2 + A_3)] \bullet (TD1 + \tau1) + [A_2/(A_1 + A_2 + A_3)] \bullet (TD2 + \tau2) + [A_3/(A_1 + A_2 + A_3)] \bullet (TD3 + \tau3)$.

Table 5. The final best physiological and statistical fitting models and their exponential mathematical models, that characterised the (τ2) phase two off-transient $\dot{V}O_2$ during submaximal (moderate and heavy) exercise in eight young adult men.

Exponential mathematical model	Fitting model	$\tau\Phi\ \dot{V}_2O_2$
	Moderate (50 Watts*, 80 %$\dot{V}_E$T**,***) and heavy (***120 %$\dot{V}_E$T) intensity exercises	
$\dot{V}O_2(t) = A_0 + A_1 \bullet [1-e^{-[(t-TD1)/\tau2]}] + A_2 \bullet [1-e^{-[(t-TD2)/\tau2]}]$	*2C,7P$_{Baseline\ 1\ min \rightarrow 6\ min\ Exercise\ Recovery}$	τ "Φ_1", $_{Stat\ \&\ Phys}$ $\tau\Phi_{2\ Isolated}$ ∴ $_{Stat\ \&\ Phys}$ $\tau_{2\ Isolated}O_2(t) = A_0 + A_2 \bullet [1-e^{-[(t-TD2)/\tau2]}]$
$\dot{V}O_2(t) = [A_0] + A_2 \bullet [1-e^{-[(t-TD2)/\tau2]}]$	*,**1C,4P$_{0.3333\ min \rightarrow 6\ min\ Exercise\ Recovery}$	τ "$\Phi_{1\ Omitted}$", $_{Stat}$ $\tau\Phi_{2\ Semi\text{-}Isolated}$ ∴ $_{Stat}$ $\Phi_{2\ Semi\text{-}Isolated}O_2(t) = A_2 \bullet [1-e^{-[(t-TD2)/\tau2]}]$
$\dot{V}O_2(t) = [A_0] + A_1 \bullet [1-e^{-[(t-TD1)/\tau2]}] + A_2 \bullet [1-e^{-[(t-TD2)/\tau2]}]$	***2C,7P$_{0.3333\ min \rightarrow 6\ min\ Exercise\ Recovery}$	τ "$\Phi_{1\ Omitted}$", $_{Stat}$ $\tau\Phi_{2\ Semi\text{-}Isolated}$ ∴ $_{Stat}$ $\Phi_{2\ Semi\text{-}Isolated}O_2(t) = A_2 \bullet [1-e^{-[(t-TD2)/\tau2]}]$

Exercise transient $\dot{V}O_2$: pulmonary $\dot{V}O_2$ uptake ($\dot{V}O_2$) corporal response from the end (off) of the exercise of an application of an ergometric forced function to the 6 min end exercise recovery. $_E$T: estimated lactate threshold. Stat: statistically significant based on Fisher's test. Phys: Physiological sense based on the differentiation of the phases and the numeric values of the estimated temporal parameters, of the transient $\dot{V}O_2$ response, according to the intensity of the exercise modelled. $\dot{V}O_2$(t) and its parameters description as in table 1. $\dot{V}O_2(t) = A_0 + A1 \bullet (1-e^{-((t-TD1)/\tau1)}) + A2 \bullet (1-e^{-((t-T2)/\tau2)})$: Two components (TD1, TD2) model with seven parameters (2C,7P). $\dot{V}O_2(t) = [A_0] + A2 \bullet (1-e^{-((t-T2)/\tau2)})$: One component model. Models fitting 20 s after de offset omitted Φ_1.The Φ means that even the mathematical exponential model fit the entire experimental data, phase one (Φ_1) did not behave in an exponential way.

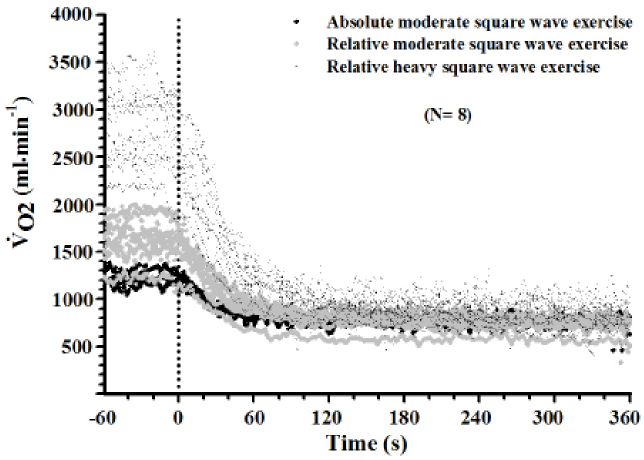

Figure 1. *Group off-transient pulmonary oxygen uptake ($\dot{V}O_2$) response profiles to absolute moderate (50 W), relative moderate (80%$\dot{V}_E$T), and relative heavy (120%$\dot{V}_E$T) square wave exercise. Exercise offset (start) is at zero min. Data points (symbols) are the breath-by-breath interpolated to second-by-second pulmonary $\dot{V}O_2$ (experimental data) from one min (-60) baseline. The eight subjects submaximal exercise at each intensity (N = 8) are displayed.*

(Tables 4-5) from the entire response for ModAbs exercise (Figure 2). On the other hand from all of those models fitting data of response omitting off Φ_1 $\dot{V}O_2$, the model A (1C,4P$_{0.3333\ min \rightarrow 6\ min}$) was the best Stat on semi-isolating off Φ_2 $\dot{V}O_2$ and its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ semi-isolated) (Tables 4-5) from this transient of response for ModAbs exercise (Figure 2).

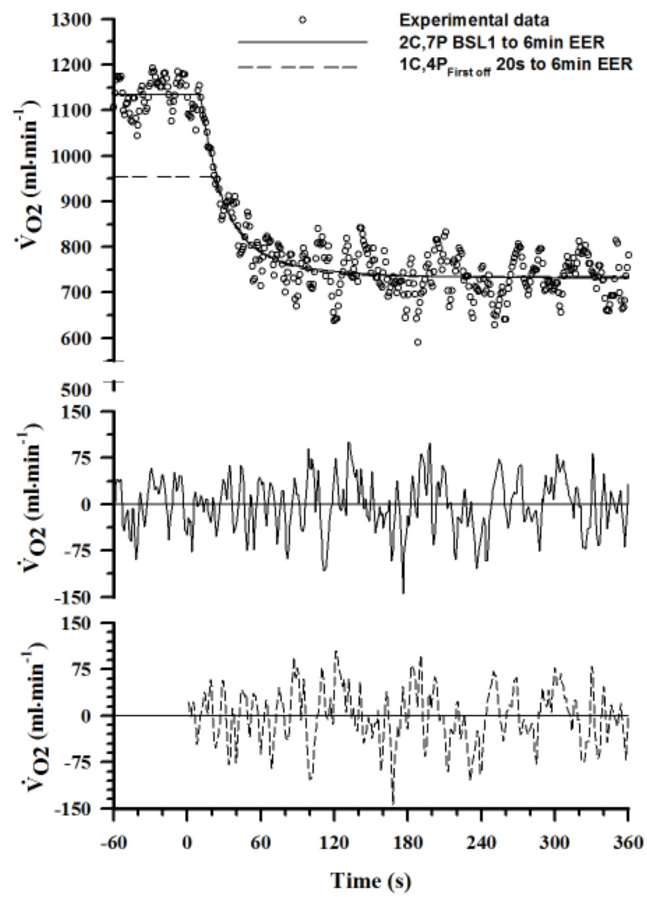

Figure 2. *Modelling of the pulmonary oxygen uptake ($\dot{V}O_2$) off-transient response to absolute moderate (50W) exercise, for a representative subject, including the corresponding residual plots from both the doble-exponential model fitting the entire response with seven parameters (2C,7P$_{BSL1 \rightarrow 6min\ EER}$) and the monoexponential model with four parameters fitting omitting (first off 20 s) phase one (1C,4P$_{0.3333min \rightarrow 6min\ EER}$) data of response. BSL1 is of one min duration (-60 s). Exercise offset (start) is at zero seconds. End post-exercise recovery (EER) is at 360 s (six min). Symbols, breath-by-breath interpolated to second-by-second pulmonary $\dot{V}O_2$ (experimental data).*

Relative moderate intensity (ModRel) exercise

$\dot{V}O_2$ off-transient response to ModRel (80%$\dot{V}_E$T) exercise was Stat ($P < 0.05$) best fitted by model A compared models B, D and G (Table 3) but models C and F were Stat ($P < 0.05$) best compared model A (Table 3) and also model F was Stat superior ($P < 0.05$) compared model B (Table 3) but B did not distinguish more than one transient phase of response. Model A fitted same as model E (Table 3) and their residuals behaved same around zero when they were applied for ModRel exercise (Figure 3). On fitting $\dot{V}O_2$ off-transient response to ModRel exercise model A was superior compared model D (Table 3) besides model D did not distinguish the end Φ_2 and the start of the steady-state $\dot{V}O_2$ off-exercise for ModAbs. Model E (2C,7P$_{0.3333\ min \rightarrow 6\ min}$) fitted Stat same as did model A (Table 3); nevertheless, the residuals of model E presented a systematic positive and negative regions around zero when it was applied for ModRel exercise (Figure 3). Both models E and F resulted Stat ($P < 0.05$) best compared model G (Table 3). Even model E fitted Stat same as did model F (Table 3); however, since the off Φ_1 $\dot{V}O_2$ residuals fluctuated randomly around zero with model F (Figure 3) then the residuals presented systematic positive and negative regions when the models E and A were applied (Figure 3). Nevertheless, the off Φ_2 $\dot{V}O_2$ amplitude of models E and F resulted significantly ($P < 0.05$) low compared those from model A (Table 4). The off $\Phi_2\dot{V}O_2$ kinetics ($\tau 2$) from model A was similar to $\tau 2$ from model E for ModRel exercise (Table 4).

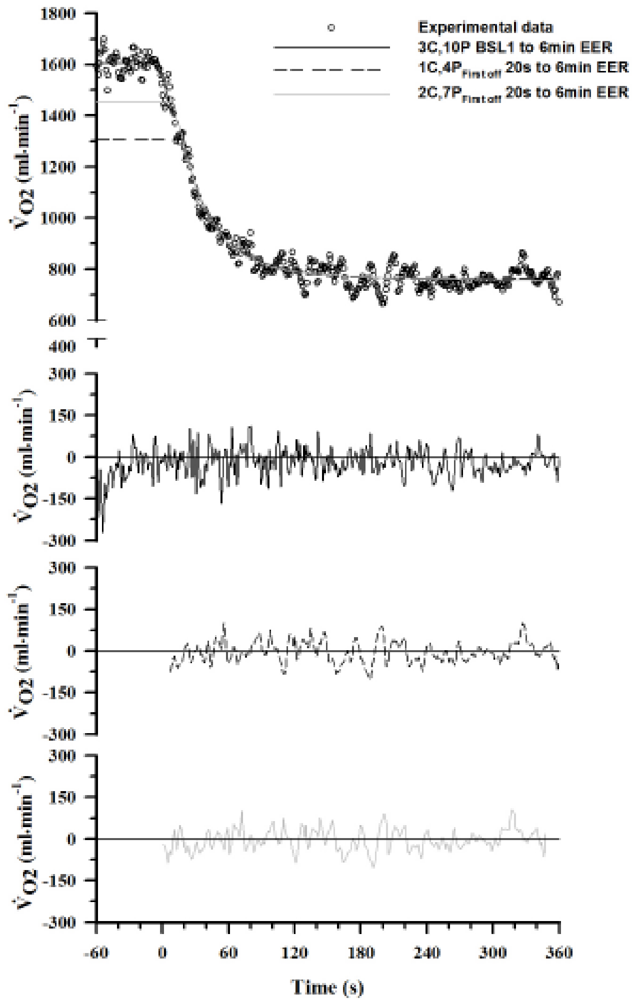

Figure 3. *Modelling of the pulmonary oxygen uptake ($\dot{V}O_2$) off-transient response to relative moderate (80%$\dot{V}_ET$) exercise, for a representative subject, including the corresponding residual plots from the triple-exponential model with 10 parameters (3C,10P$_{BSL1 \rightarrow 6min\ ERE}$) fitting the entire response, both the doble-exponential model with seven parameters fitting either the entire response (2C,7P$_{BSL1 \rightarrow 6min\ EER}$) or omitting phase one (first off 20 s) (2C,7P$_{0.3333min \rightarrow 6min\ EER}$) data of response, and also the mono-exponential model with four parameters fitting omitting phase one (1C,4P$_{0.3333min \rightarrow 6min\ EER}$) of response. BSL1 is of one min duration (-60 s). Exercise offset (start) is at zero seconds. End post-exercise recovery (EER) is at 360 s (6 min). Symbols, as in Figure 2. $\dot{V}_ET$: ventilatory threshold.*

Thus, either the model A and the model E, by omitting off Φ_1 $\dot{V}O_2$, (1C,4P$_{0.3333 \rightarrow 6\ min}$) were best Stat on semi-isolating off Φ_2 $\dot{V}O_2$ and its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$) (Tables 4-5) omitting off Φ_1 $\dot{V}O_2$ (Figure 3) from the transient of response for ModRel exercise in this study.

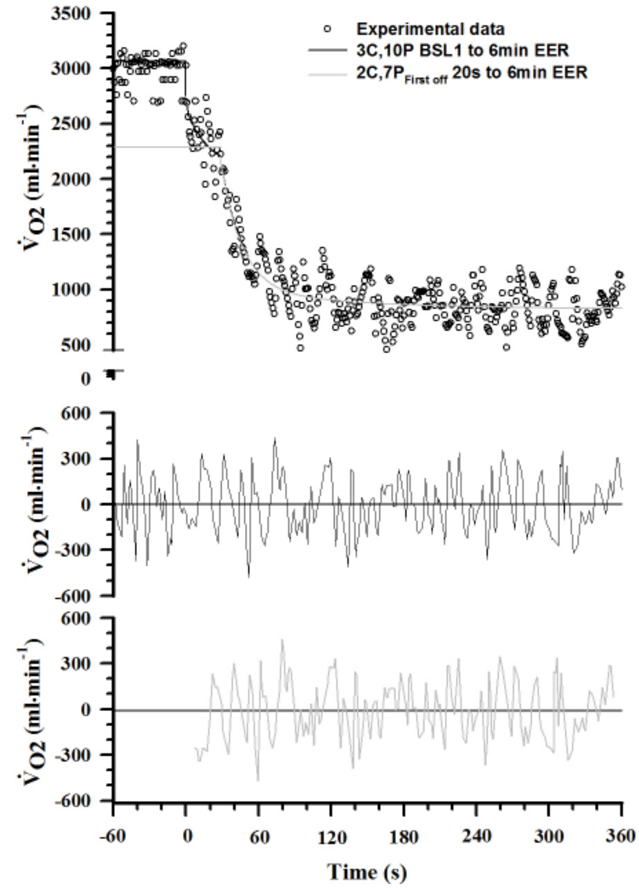

Figure 4. *Modelling of the pulmonary oxygen uptake ($\dot{V}O_2$) off-transient response to relative heavy (120%$\dot{V}_ET$) exercise, for a representative subject, including the corresponding residual plots from both the triple-exponential model with 10 parameters fitting the entire response (3C,10P$_{BSL1 \rightarrow 6min\ EER}$), and also the double-exponential model with seven parameters fitting omitting (first off 20 s) phase one (2C,7P$_{0.3333min \rightarrow 6min\ EER}$) of response. BSL1 is of one min duration (-60 s). Exercise offset (start) is at zero seconds. End post-exercise recovery (EER) is at 360 s (6 min). Symbols, as in figure 2. $\dot{V}_ET$: ventilatory threshold.*

Relative heavy intensity (HvyRel) exercise

$\dot{V}O_2$ off-transient response to HvyRel (120%$\dot{V}_ET$) exercise was Stat ($P < 0.05$) best fitted by model A compared models B and D (Table 3) but models C, E, F and G were Stat ($P < 0.05$) best compared model A (Table 3). Model B was Stat superior ($P < 0.05$) compared both models C and D only (Table 3) but model B did not distinguish more than one transient phase of response. Model F (2C,7P$_{BSL1\ min\ to\ 6\ min}$) was Stat ($p < 0.05$) best compared model E (2C,7P$_{0.3333\ min \rightarrow 6\ min}$) (Table 3). Model D, that did not distinguish the end Φ_2 and the start of the steady-state $\dot{V}O_2$ off-exercise for HvyRel, was Stat best compared both models E and F (Table 3) but model G (3C,10$P_{BSL1\ min\ to\ 6\ min}$) resulted both Stat ($P < 0.05$) and Phys (it distinguished three off-transient phases) (Figure 4) superior compared models D, E and F (Table 3) for HvyRel exercise. The off Φ_2 $\dot{V}O_2$ amplitudes of models E and G resulted similar to each other (Table 4); the off Φ_2 $\dot{V}O_2$ TD of model E resulted significantly ($P < 0.05$) low compared that from model G (Table 4) and; the off Φ_2 $\dot{V}O_2$ kinetics ($\tau 2$) from models E and G resulted similar to each other (Table 4) for HvyRel exercise. Thus, on one side the model G (3C,10$P_{BSL1\ min\ to\ 6\ min}$) was the best both Stat and Phys on isolating off Φ_2 $\dot{V}O_2$ and its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$) (Tables 4-5) from the entire response for HvyRel exercise (Figure 4). On the other side from all of those models fitting data of response omitting off Φ_1 $\dot{V}O_2$, the model E (2C,7$P_{0.3333\ min \to 6\ min}$) was the best Stat on semi-isolating off Φ_2 $\dot{V}O_2$ and its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ semi-isolated) (Tables 4-5) from this transient of response for HvyRel exercise (Figure 4). However, taking in consideration that Φ_1 is frequently extremely difficult to fit then the best option should be the 2C,7$P_{0.3333\ min \to 6\ min}$ for isolating off Φ_2 $\dot{V}O_2$ and to describe its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$) for HvyRel exercise.

DISCUSSION

The subject characteristics, maximal power output, $\dot{V}O_2$ pick, and $\dot{V}_ET$ values were in agreement with those of healthy young males reported by Åstrand[17] and Whipp.[2] As expected, the end-exercise $\dot{V}O_2$, exercise intensity expressed as absolute power output and relative to the $\dot{V}_ET$ (% $\dot{V}_ET$) resulted significantly different to each other (50W < 80% $\dot{V}_ET$ < 120% $\dot{V}_ET$) and also did, the moderate intensity exercise slope of the subthreshold $\dot{V}O_2$ - power output relationship and the $\dot{V}O_2$ during off cycling post-exercise (recovery).[2]

Mathematical modelling

The off-transient (post-exercise recovery) $\dot{V}O_2$ response to the exercise tests for 50 W, absolute moderate (ModAbs) exercise; for 80%$_E$T, relative moderate (ModRel) exercise and; for relative heavy (HvyRel) exercise (submaximal exercise) constant off-loadless cycling was analysed with seven exponential mathematical fitting models previously published to characterise the off Φ_2 $\dot{V}O_2$ kinetics (off $\tau\Phi_2$ $\dot{V}O_2$) for this submaximal exercise. Evermore, the $\tau\Phi_2$ $\dot{V}O_2$ transient is not discernible different from that at the on-transient.[3]

Absolute moderate intensity (ModAbs) exercise

During the time course of the entire off $\dot{V}O_2$ response from the off ModAbs exercise, the double-exponential model (2C,7$P_{BSL1\ min \to 6\ min}$) identified two transient phases of response, the off Φ_1 $\dot{V}O_2$ and the off Φ_2 $\dot{V}O_2$, and characterized their kinetics (off $\tau\Phi_1$ $\dot{V}O_2$ and off $\tau\phi_2$ $\dot{V}O_2$). From these assessment with the double-exponential model, we were able to both statistically and physiologically characterize an isolated off Φ_2 $\dot{V}O_2$ and its kinetics ($\tau 2 = 25.1 \pm 8.4$ s). The off Φ_2 $\dot{V}O_2$ is an exponential $\dot{V}O_2$ decrease until a new resting steady-state level (steady-state post-exercise recovery) is reached near to the original resting $\dot{V}O_2$ level.[4] However, since at the cessation of the moderate exercise, a rapid downward shift of $\dot{V}O_2$ off-transient response (off $\tau\phi_1$ $\dot{V}O_2$) occurs, making sometimes very difficult to model the off Φ_1 $\dot{V}O_2$, then the mono-exponential model omitting (first off-20 s) off $\tau\phi_1$ $\dot{V}O_2$ (1C,4$P_{0.3333\ min \to 6\ min}$) also kinetically characterized $\tau 2$ (28 ± 4 s) for off τ_2 $\dot{V}O_2$ (semi-isolated off Φ_2 $\dot{V}O_2$); giving a $\tau 2_{off(isolated\ +\ semi-isolated)} = 26.5 \pm 6.51$ s in this study similar to that ($\tau 2_{off} = 29 \pm 6$ s) reported in the literature.[3,8,22] Thus, we preferred the isolated off $\tau\Phi_2$ $\dot{V}O_2$ with the double-exponential model rather that the semi-isolated off $\tau\Phi_2$ $\dot{V}O_2$ with the 1C,4$P_{0.3333\ min \to 6\ min}$ model for ModAbs exercise between different conditions. Besides, little is known about off $\tau\Phi_1$ $\dot{V}O_2$ duration[8]; however, because blood flow is high at the off-transient its duration is likely to be less than 20 s in post-exercise recovery[3] and that could explain our submaximal exercie $\tau 1_{off}$ values lower that 20 s (overall $\tau 1_{off} = 15.78 \pm 7.4$ s).

Relative moderate intensity (ModRel) exercise

The pulmonary oxygen uptake post-exercise recovery response ($\dot{V}O_2$ off-transient) to moderate intensity exercise (i.e., < $\dot{V}_ET$) has been characterized with a first-order, three component exponential model[4,5,18] and agreed on one side with this study with our doble-exponential model omitting off Φ_1 $\dot{V}O_2$, (2C,7$P_{0.3333\ \to 6\ min}$) on semi-isolating off Φ_2 $\dot{V}O_2$ and characterizing its kinetics (off $\tau\Phi_2$ $\dot{V}O_2 = 22.5 \pm 4.2$ s) from the off-transient of response for ModRel exercise. Evermore, in this study we explain that the 2C,7$P_{0.3333 \to 6\ min}$ was statistically superior on modelling off Φ_2 $\dot{V}O_2$ compared triple-exponential model (3C,10$P_{BSL1\ min\ to\ 6\ min}$) ($\tau 2_{off} = 23.2 \pm 6.8$ s) because we consistently found the off $\tau\Phi_1$ $\dot{V}O_2$ for ModRel was difficult to fit (TD1 = -11.0 ± 5.2) with this last model. On the other side, our model A, omitting off Φ_1 $\dot{V}O_2$, (1C,4$P_{0.3333 \to 6\ min}$) was the best Stat on semi-isolating off Φ_2 $\dot{V}O_2$ and its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ = (off $\tau\Phi_2$ $\dot{V}O_2$ = 31.2 ± 5.3 s) omitting off Φ_1 $\dot{V}O_2$ for the transient of response for ModRel exercise in this study, that also agreed with Özyener, *et al.*[3] in that they found that the monoexponential model omitting off phase one was adequate to characterize the off-transient response for the moderate exercise intensity. In this sense ModRel (80% $\dot{V}_E$T) modeled different compared ModAbs (50 W).

Moderate (Mod) intensity exercise

The $\dot{V}O_2$ off-transient to moderate intensity exercise has been characterized[3,22] with the mono-exponential model omitting off phase one for this off-transient response and agreed with this study with our mono-exponential model omitting off Φ_1 $\dot{V}O_2$ (1C,4P$_{0.3333 \rightarrow 6\ min}$) semi-isolated off Φ_2 $\dot{V}O_2$ and characterized its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$) from the off-transient of response for Mod (Abs and Rel) exercise. In this study we observed that the time course of the entire off $\dot{V}O_2$ response from the ModAbs (50 W = 62% $\dot{V}_E$T) exercise modeled different compared that from ModRel (80% $\dot{V}_E$T) in our young male group; that is, even both work rate exercise intensities were (< $\dot{V}_E$T), ModAbs off $\dot{V}O_2$ data of response was best fitted either a double exponential model or a mono-exponential model omitting phase one off $\dot{V}O_2$ the ModRel was only statistically best fitted by the mono-exponential model omitting phase one off $\dot{V}O_2$; physiologically meaning that on one side the entire off $\dot{V}O_2$ response from the Mod (Abs and Rel) showed two transient phases (off Φ_1 $\dot{V}O_2$ and off Φ_2 $\dot{V}O_2$) kinetically characterized (off $\tau\Phi_1$ $\dot{V}O_2$ = 16.7 ± 9.0 s and off $\tau\Phi_2$ $\dot{V}O_2$) toward end post-exercise recovery, the entire off $\dot{V}O_2$ response from the ModRel modeled with the triple exponential model showed three transient phases (off Φ_1 $\dot{V}O_2$, off Φ_2 $\dot{V}O_2$ and off Φ_3 $\dot{V}O_2$) kinetically characterized (off $\tau\Phi_1$ $\dot{V}O_2$ = 23.54 ± 8.9 s, off $\tau\Phi_2$ $\dot{V}O_2$ and off $\tau\Phi_3$ $\dot{V}O_2$ = 141.0 ± 10.0 s) towards end post-exercise recovery. That explain why, the model 2C,7P$_{0.3333 \rightarrow 6\ min}$ omitting the off $\tau\Phi$Ö$_1$ $\dot{V}O_2$ of response fitted best as well as for ModRel intensity exercise in agreement with fitting off-transient $\dot{V}O_2$ moderate exercise response omitting phase one (first off -20 s) by Whipp,[4] Linnarsson,[5] Cunningham, *et al.*[18] and Özyener, *et al.*[3] despite we did not model as they did[18] on data at 10 s intervals with a single-, and double-exponential model with one time delay, and also expressing amplitudes in terms of functional gains. However, perhaps because of the different way of modeling by Özyener, *et al.*[3] they found that the mono-exponential model omitting off phase one was adequate to characterize the off-transient responses for the moderate (for Mod only in this study) and heavy exercise (not the case in our study) intensities. In this study, the off $\tau\Phi_2$ $\dot{V}O_2$ = 25.18 ± 6.06 from the best fitting models for Mod exercise was similar to the off $\tau\Phi_2$ $\dot{V}O_2$ by Özyener, *et al.*[3] who suggested that variability could be related to metabolism itself, rather than to factors such as variations in pedalling frequency, additional work performed by upper limb muscles, or other extraneous sources of metabolic demand.[3]

Relative heavy intensity (HvyRel) exercise

For heavy exercise (i.e. > $\dot{V}_E$T), the $\dot{V}O_2$ dynamics are more complex and require a second-order model,[6,7] for appropriate characterization as a result of a slow kinetic component ($\tau\Phi_3$ $\dot{V}O_2$) which supplements the fundamental component (Φ_2 $\dot{V}O_2$) suggesting a more complex link between muscle force production and the metabolic mechanisms of energy transfer at a work rate above $\dot{V}_E$T.[22] This Φ_3 $\dot{V}O_2$ is often less evident at the off-transient[19,20] such that the off-transient $\dot{V}O_2$ kinetics can retain first-order characteristics (i.e., off Φ_2 $\dot{V}O_2$) even for work rate above $\dot{V}_E$T at least in the heavy intensity domain[6] explaining partially why in this study the entire $\dot{V}O_2$ off-transient response to HvyRel (120%$\dot{V}_E$T) exercise was both statistically and physiologically best fitted by the triple-exponential model (3C,10P$_{BSL1\ min\ to\ 6\ min}$) identifying its three off $\dot{V}O_2$ phases (off Φ_1 $\dot{V}O_2$, off Φ_2 $\dot{V}O_2$ and off Φ_3 $\dot{V}O_2$) and by characterizing their kinetics (off $\tau\Phi_1$ $\dot{V}O_2$, off $\tau\Phi_2$ $\dot{V}O_2$ and off $\tau\Phi_3$ $\dot{V}O_2$) isolating the off Φ_2 $\dot{V}O_2$ kinetics (off $\tau\Phi_2$ $\dot{V}O_2$). Thus, on fitting $\dot{V}O_2$ off-transient response to HvyRel exercise data of response omitting off Φ_1 $\dot{V}O_2$, the double-exponential model (2C,7P$_{0.3333\ min \rightarrow 6\ min}$) was the best statistically on semi-isolating off Φ_2 $\dot{V}O_2$ and its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ semi-isolated). Evermore, in agree with these observations, this $\dot{V}O_2$ off-transient response was found to be well described by either a mono-exponential function or a double exponential incorporating a slow component because the off-transient $\dot{V}O_2$ kinetics may retain first-order characteristics, despite the work rate exceeding $\dot{V}_E$T.[5,6,19 20,21] However, Cunningham, *et al.*[8] showed that the offtransient $\dot{V}O_2$ kinetics were shown to be independent of the on-transient slow-component contribution but that the mechanisms proportionally coupled to the absolute $\dot{V}O_2$ achieved seems to be the dominant influence on the order of the off-transient kinetics.[3] In this study, in partial agreement with Özyener, *et al.*[3] the off-transient time constant of the fundamental $\dot{V}O_2$ component ($\tau2_{off}$) from those best fitting models (except the 3C,10P$_{BSL1\ min\ to\ 6\ min}$) did not vary significantly among our three work (except for HvyRel) intensities. We explain our high off $\tau\Phi_2$ $\dot{V}O_2$ for HvyRel exercise compared the off $\tau\Phi_2$ $\dot{V}O_2$ value for Rel because even the $3C,10P_{BSL1\ min\ to\ 6\ min}$ model fitted statistically and physiologically best HvyRel exercise; however it did it, with a negative off phase one TD and high off phase TD2 and perhaps this explain why they[3] characterised the off $\tau\Phi_2$ $\dot{V}O_2$ work rate very exceeding $\dot{V}_ET$ with a double-exponential with no delay. In consequence, by omitting off phase one the two-exponential model (including TD) is preferred on modelling the off-transient $\dot{V}O_2$ dynamics exceeding $\dot{V}_ET$ work rate exercise.

In brief, the $\dot{V}O_2$ off-transient entire response for ModAbs exercise were well described by model F ($2C,7P_{BSL1\ min\rightarrow 6\ min}$) allowed the off Φ_2 $\dot{V}O_2$ isolation and characterized their kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ = 25 $\pm$ 8 s). The model A ($1C,4P_{0.3333\ min\rightarrow 6\ min}$) omitting off Φ_1 $\dot{V}O_2$ semi-isolated off Φ_2 $\dot{V}O_2$ and kinetically characterized off τ_2 $\dot{V}O_2$ [τ2 (28 $\pm$ 4 s)] for ModAbs exercise ($\tau 2_{off(A\ +F)}$ = 26.5 $\pm$ 6.5 s). For ModRel the model E ($2C,7P_{0.3333\rightarrow 6\ min}$) omitting off Φ_1 $\dot{V}O_2$ well described this semi-isolated off Φ_2 $\dot{V}O_2$ and characterized its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ = 22.5 $\pm$ 4.2 s). The $\tau 2_{off\ moderate\ intensity\ exercise}$ = 25.2 $\pm$ 6.1 s. For HvyRel exercise model E ($2C,7P_{0.3333\rightarrow 6\ min}$) omitting off f_1 $\dot{V}O_2$ semi-isolated off Φ_2 $\dot{V}O_2$ and well characterized its kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ = 22.8 $\pm$ 6 s). Our $\tau 2_{off\ (omitting\ \Phi 1\ O2)\ submaximal\ intensity\ exercise}$ value (24.42 $\pm$ 5.30 s) agreed inside the τ2 $\dot{V}O_2$ typically range of the order of 30-40 s in healthy young individuals.[23]

CONCLUSIONS

The pulmonary oxygen uptake post-exercise recovery entire response ($\dot{V}O_2$ off-transient) for absolute moderate intensity exercise were well described by a double-exponential function, allowed the off Φ_2 $\dot{V}O_2$ isolation and characterized their kinetics (off $\tau\Phi_2$ $\dot{V}O_2$ = 25 $\pm$ 8 s). A mono-exponential function omitting off Φ_1 $\dot{V}O_2$ and semi-isolateting off Φ_2 $\dot{V}O_2$, kinetically characterized off Φ_2 $\dot{V}O_2$ (τ2 = 28 $\pm$ 4 s) for absolute moderate intensity exercise ($\tau 2_{off(isolated\ +\ semi\text{-}isolated)}$ = 26.5 $\pm$ 6.5 s). A double-exponential function omitting off Φ_1 $\dot{V}O_2$ well described the semi-isolated off Φ_2 $\dot{V}O_2$ and characterized its kinetics for either relative moderate intensity exercise (off $\tau\Phi_2$ $\dot{V}O_2$ = 22.5 $\pm$ 4.2 s) or for heavy moderate intensity exercise (off $\tau\Phi_2$ $\dot{V}O_2$ = 22.8 $\pm$ 6 s). The fundamental off Φ_2 $\dot{V}O_2$ from these best fitting models that omitted Φ_1 $\dot{V}O_2$, well described its kinetics for submaximal post-exercise recovery (τ2 = 24.42 $\pm$ 5.30 s). When modelling makes physiological sense for the entire (complete) off $\dot{V}O_2$ response of submaximal exercise, the double-exponential function and the triple-exponential function models are preferred to statistically and physiologically isolate, the off $\tau\Phi_2$ $\dot{V}O_2$ of the exercise for moderate intensity- and heavy intensity-exercise, respectively.

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REFERENCES

1. Dempsey JA, Vudruk EH, Mastenbrook SM. Pulmonary control systems in exercise: Update Fed Proc 1985; 44: 1498-505.
2. Whipp BJ. The bioenergetics and gas exchange basis of exercise testing. Clin Chest Med 1994: 15: 173-92.
3. Özyener F, Rossiter HB, Ward SA, Whipp BJ. Influence of exercise intensity on the on- and offtransient kinetics of pulmonary oxygen uptake in humans. J Physiol 2001: 533.3: 891-902.
4. Whipp BJ, Ward SA, Lamarra N, Davis JA, Wasserman K. Parameters of ventilatory and gas exchange dynamics during exercise. J Appl Physiol 1982; 52: 1506-13.
5. Linnarsson D. Dynamics of pulmonary gas exchange and heart rate changes at start and end of exercise. Acta Physiol Scand 1974; (Suppl. 415): 1-68.
6. Paterson DH, Whipp BJ. Assymetries of oxygen uptake transients at the on- and off-set of heavy exercise in humans. J Physiol 1991; 443: 575-86.
7. Barstow TJ, Molé PA. Linear and nonlinear characteristics of oxygen uptake kinetics during heavy exercise. J Appl Physiol 1991; 71: 2099-106.
8. Cunningham DA, St Croix JM, Özyener F, Whipp BJ. The off-transient pulmonary oxygen uptake ($\dot{V}O_2$) kinetics following attainment of a particular $\dot{V}O_2$ during heavy-intensity exercise in humans. Exp Physiol (London) 2000; 85: 339-47.
9. Davis JA, Frank MH, Whipp BJ, Wasserman K. Anaerobic threshold alterations caused by endurance training in middle-aged men. J App Physiol 1979; 46:1039-46.
10. Whipp BJ, Davis JA, Torres F, Wasserman K. A test to determine parameters of aerobic function during exercise. J App Physiol 1981; 50: 217-21.
11. Beaver WL, Lamarra N, Wasserman K. Breath-by-breath measurements of true alveolar gas exchange. J Appl Physiol 1981; 51:1662-75.

12. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting the anaerobic threshold by gas exchange. J Appl Physiol 1986; 60: 2020-7.
13. Wasserman K, Whipp BJ, Koyal SN, Beaver WL. The anaerobic threshold and respiratory gas exchange during exercise. J Appl Physiol 1973; 35: 236-42.
14. Padilla JP, Kowalchuk JM, Taylor AW, Paterson DH. Determinación de la cinética de la fase dos transitoria de la O_2 durante ejercicio de carga constante de intensidades moderada e intensa en hombres jóvenes. *Rev* Hosp Jua Mex 2007; 74(4): 231-44.
15. Motulsky HJ, Ransnas LA. Fitting curves to data using nonlinear regression: a practical and nonmathematical review. FASEB J 1987; 1: 365-74.
16. Zar JH. Biostatistical analysis. 3rd Ed. New Jersey, USA. Englewood Cliffs: Prentice-Hall; 1996, p. 162-473.
17. Åstrand I. Aerobic work capacity in men and women with special reference to age. Acta Physiol Scand 1960; 49 (Suppl. 169).
18. Cunningham DA, Himann JE, Paterson DH, Dickinson JR. Gas exchange dynamics with sinusoidal work in young and elderly women. Resp Physiol 1993; 91: 43-56.
19. Gerbino A, Ward SA, Whipp BJ. Effects of prior exercise on pulmonary gas-exchange kinetics during high-intensity exercise in humans. J Appl Physiol 1996; 80: 99-107.
20. Bohnert B, Ward SA, Whipp BJ. Effects of prior arm exercise on pulmonary gas exchange kinetics during high-intensity leg exercise in humans. Exp Physiol 1998; 83: 557-70.
21. Langsetmo I, Poole DC. O_2 recovery in the horse following moderate, heavy and severe exercise. J Appl Physiol 1999; 86: 1170-7.
22. Rossiter HB, Ward SA, Kowalchuk JM, Howe FA, Griffiths JR, Whipp BJ. Dynamic asymmetry of phosphocreatine concentration and O_2 uptake between the on- and off-transients of moderate and high-intensity exercise in humans. J Physiol 2002; 541(3): 991-1002.
23. Whipp BJ, Rossiter HB, Ward SA. Exertional oxygen uptake kinetics: a stamen of stamina? Biochem Soc Trans 2002; 30(2): 237-47.

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