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Fitting a Single-Phase Model to the Post-Exercise Changes in Heart Rate and Oxygen Uptake

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Summary

The kinetics of post-exercise heart rate (HR) and oxygen consumption (EPOC) was studied in 10 elite cyclists subjected to four laboratory cycle ergometer maximal exercises lasting 30, 90, 180 or 360 s. Heart rate and oxygen uptake (VO_2) were recorded over a period of 6 min after the exercise. By applying the logit transformation to the recorded variables and relating them to the decimal logarithm of the recovery time, uniform single-phase courses of changes were shown for both variables in all subjects and exercises. This enabled computing half-recovery times ($t_{½}$) for both variables. Half-time for VO_2 negatively correlated with square root of exercise duration (within-subject $r=-0.629$, $p<0.001$), the total post-exercise oxygen uptake till $t_{½}$ was thus constant irrespectively of exercise intensity. The method is simple and enables reliable comparisons of various modes of exercise with respect to the rate of recovery.

Key words

Post-exercise recovery • Heart rate • Oxygen uptake • Half-recovery time

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Introduction

Physical exercise, especially an intense one, brings about a disturbance in homeostasis, leading to fatigue. The resulting changes are compensated during the recovery period. The post-exercise recovery consists of eliminating metabolic products, resynthesis of energy substrates, lowering body temperature, normalizing the water and electrolyte equilibrium, oxygen consumption, etc. An adequate recovery is essential for resuming work; hence the rates of recovery processes determine the overall performance of interval work.

Recovery-associated changes in excess post-exercise oxygen consumption (EPOC) are believed to proceed in a biphasic manner, as follows from simple exponential plots (log VO_2 vs. time), and faster in trained than in untrained subjects (Short and Sedlock 1997). That biphasic model, i.e. consisting of "fast" and "slow" components, has been acknowledged as the standing one, as presented in all modern textbooks (Åstrand *et al.* 2003, Powers and Howley 1996).

However, application of the exponential model to the post-exercise processes might be disputable since metabolic processes like lactate elimination could follow rather the mass action law, and not an exponential decay. Therefore, alternative models based on the mass action law might be considered to fit the experimental data.

In case of oxygen uptake, such model would involve the net maximum post-exercise uptake ($OC_{max} - OC_{rest}$); during the recovery, oxygen uptake decreases and, at given moment, includes two components: the residual "oxygen debt" ($OC_i - OC_{rest}$) and the "oxygen debt" already paid ($OC_{max} - OC_i$). Of course, the mass action law would apply only formally, and in the case of rendering a linear relationship would facilitate various comparisons and not necessarily provide causal explanations. The aim of this study was thus to apply the logit-log model, used e.g. in radioimmunoassays (Stupnicki 1982), in order to evaluate the course of changes in the excess post-exercise heart rate and oxygen uptake.

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Table 1. Variables recorded in cycle ergometer exercises (n=10).

Variable	Exercise duration			
	30 s	**90 s**	**180 s**	**360 s**
Work output (kJ·kg^{-1})	0.29 ± 0.01	0.71 ± 0.11	1.19 ± 0.11	1.91 ± 0.20
max HR, net (bpm)	104.2 ± 11.8	104.6 ± 5.9	109.1 ± 10.3*	118.8 ± 13.0*
max VO$_2$, net (ml·min^{-1}·kg^{-1})	49.0 ± 3.5*	57.1 ± 4.5*	59.4 ± 4.8*	66.0 ± 5.6*
$t_{½HR}$ (s)	101.8 ± 59.2	128.9 ± 64.9	119.8 ± 42.0	122.3 ± 36.0
$t_{½VO_2}$ (s)	42.8 ± 9.9*	36.4 ± 5.2	34.3 ± 5.0	30.5 ± 5.3*
Total O$_2$ uptake till $t_{½}$	25.9 ± 6.7	25.3 ± 2.6	27.1 ± 4.8	25.7 ± 4.3

Data are mean values ± SD. * Significantly (p<0.05) different from the respective values in other exercise durations.

Material and methods

Subjects

A group of 10 professional cyclists were studied. Their age ranged from 21 to 32 years, body height from 174 to 185 cm, body mass from 66 to 83 kg, athletic experience 9 to 20 years. They were subjected to 5 laboratory exercises on Monark 824 cycle ergometer, preceded by a warm-up lasting 3 min, at a load of 75 W.

All subjects gave their informed consent to participate in the study, which was approved by the local Ethics Committee.

Methods

The following exercise tests were applied:

1) Conventional, 30 s Wingate test at a load equal to 7.5 % of body mass (Bar-Or 1987);
2) Maximal, 90 s exercise at an intensity equal to 130 % of power output at VO_2max;
3) Volitionally maximal, 180 s exercise at an intensity equal to 115 % of power output at VO_2max;
4) Volitionally maximal, 360 s exercise at an intensity equal to 100 % of power output at VO_2max.

During the tests and throughout 6 min after each test had been terminated, oxygen uptake (VO_2) and heart rate (HR) were recorded using Vmax29 Spectra gas analyzer (Sensormedic, USA) and sport tester (Team Polar, Finland), respectively. Values of VO_2 and HR recorded at the moment of terminating the exercise were considered the initial ones for the post-exercise recovery following given test (max VO_2 and max HR, respectively). Pre-exercise values, recorded following a 10-min rest preceding the warm-up, were subtracted from all subsequent ones, rendering net values which were subsequently converted to decimal logits according to the formula

$$\text{logit}(x_i) = \log(\frac{x_i}{x_m - x_i}),$$

where x_i is the net value of HR or VO_2 at time point *i*, and x_m is the max HR or max VO_2, i.e. the net maximum value after the exercise has been terminated.

Data analysis

Data analysis was applied to net values only; heart rate and oxygen uptake data were subjected to decimal logit transformation and related to log time. The following procedures were used: two-way ANOVA (followed by *post-hoc* Scheffé's test when necessary) and linear regression. Coefficients of variability (raw data) and Pearson's coefficients of correlation between studied variables were calculated. The level of $p \leq 0.05$ was considered significant.

Results

Mean values (± SD) of heart rate and VO_2 (net) and those of derived indices are presented in Table 1. The mean pre-exercise values of HR and VO_2 were 68.5±7.2 and 6.4±1.3, respectively.

Mean values (± SD) of heart rate and VO_2 vs. time, recorded in 10 cyclists during post-exercise recovery, are presented in Figure 1, mean logarithms of net values of HR or VO_2 plotted vs. time are shown in Figure 2 and mean logits plotted vs. log time are presented in Figure 3. All graphs pertain only to the 30 s Wingate test as the courses of changes were in all kinds of exercise alike.

When the data were plotted in the conventional way (log value vs. time), biphasic courses were obtained and the breakpoints for both HR and VO_2 (Fig. 2)

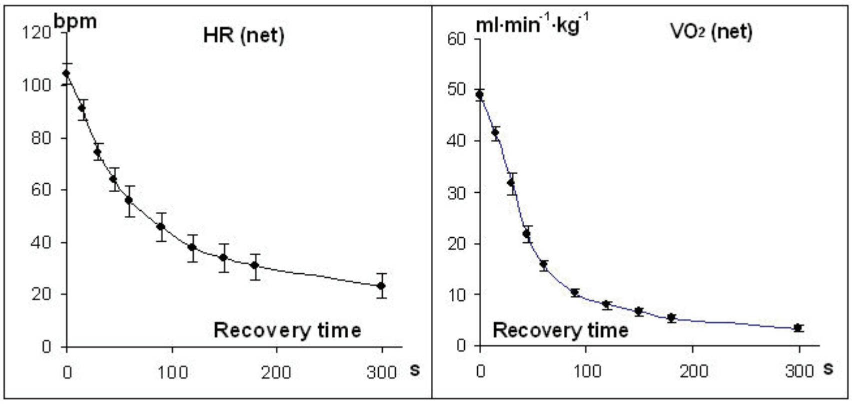

Fig. 1. Mean values (± SE) of net oxygen uptake (VO_2) and of net heart rate (HR) during post-exercise (30 s Wingate test) recovery in male cyclists (n=10).

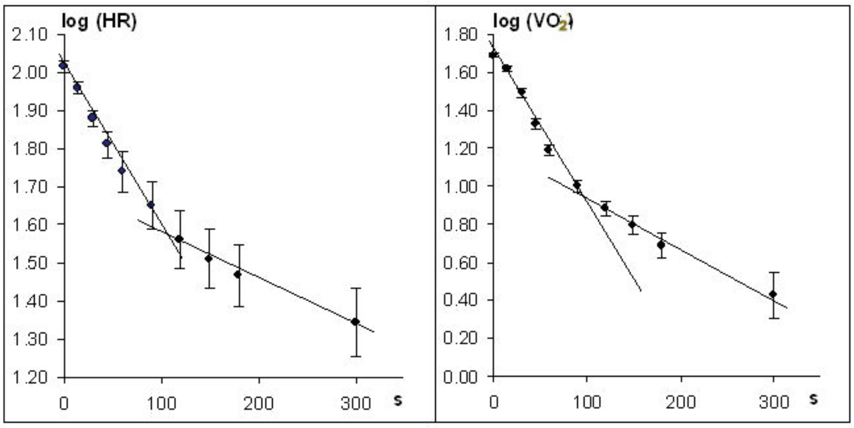

Fig. 2. Log VO_2 and log HR vs. time (means ± SE) for post-exercise (30 s Wingate test) recovery in male cyclists (n=10).

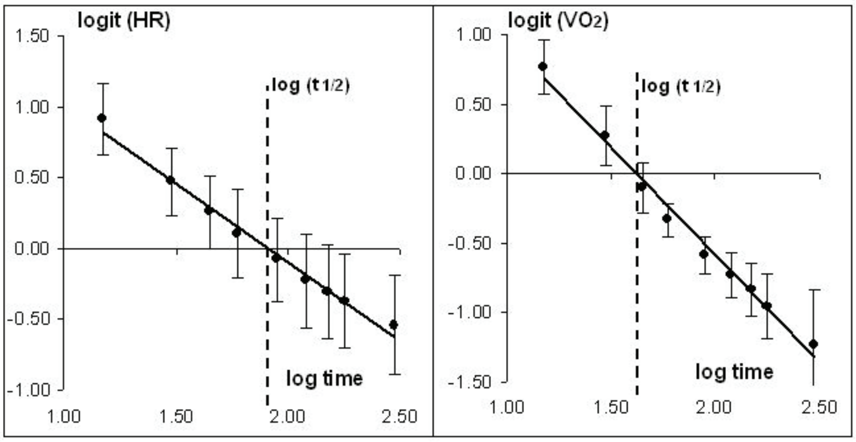

Fig. 3. Logit VO_2 and logit HR vs. log recovery time (means ± SE) for post-exercise (30 s Wingate test) recovery in male cyclists (n=10). The value of log time at logit = 0 corresponds to log half-recovery time (log $t_{½}$).

occurred at about 95 s. In contrast, the logit-log plots of net data (Fig. 3) rendered single-phase courses. Half-recovery times ($t_{½}$) may be easily computed from those graphs, for log ($t_{½}$) corresponds to logit = 0. For the standard 30-s exercise it amounted to 43 and 102 s for HR and VO_2, respectively (Table 1).

All maximum and $t_{½}$ values showed highly significant ($p<0.001$) between-subject variability by two-way ANOVA ($F_{9,27}$ values ranging from 4.0 to 10.3). Mean maximum, as well as $t_{½VO_2}$ values, varied with exercise duration. The max HR increased linearly vs. exercise time; max VO_2 increased, and $t_{½VO_2}$ correspondingly decreased linearly vs. square root of exercise time. The values of $t_{½HR}$ proved to be highly variable both within and between subjects; for example, in the 30 s exercise, individual values ranged from 40 to 243 s and no significant differences between exercises were found. No significant differences between exercises were found for the total O_2 uptake till half-recovery time. Coefficients of variability for maximum values of HR and VO_2 were low and amounted to about 8 %, those for $t_{½VO_2}$ and total O_2 uptake till half-recovery time were

Table 2. Residual (within-subject) coefficients of correlation between studied variables (df=29). Heart rate and oxygen uptake are net values.

Correlated variables	**max VO_2**	**$t_{½HR}$**	**$t_{½VO_2}$**	**Exercise duration (s)**
max HR, net (bpm)	0.716***	0.359*	–0.401*	0.766***
max VO_2, net ($ml \cdot min^{-1} \cdot kg^{-1}$)		0.261	–0.675***	0.907***
$t_{½HR}$ (s)			–0.236	0.001
$t_{½VO_2}$ (s)				–0.629***

Square root of exercise duration was taken for VO_2 and $t_{½VO_2}$. * p<0.05; ** p<0.01; *** p<0.001.

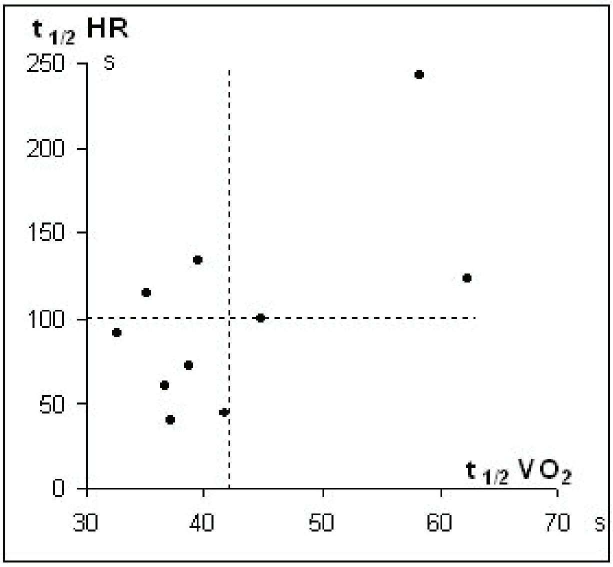

Fig. 4. Plot of half-recovery times (s) for post-exercise (30 s Wingate test) heart rate vs. oxygen uptake in male cyclists (n=10). Dashed lines are mean values of both variables.

somewhat higher amounting to about 17 %, while in the case of $t_{½HR}$ they were very high and decreased with exercise duration from 58 to 29 % for 30-s and 360-s exertions, respectively.

The residual (within-subject) coefficients of correlations between the studied variables were computed (Table 2). The half-recovery time for HR ($t_{½HR}$) did not correlate significantly with either $t_{½VO_2}$ or exercise duration. Maximum values of VO_2 significantly correlated with the respective $t_{½}$ values ($r = –0.675$; $p<0.001$) for all exercises combined (n=40) and the same was true for max HR ($r = 0.359$; $p<0.05$). Maximum values of VO_2 significantly correlated with those of HR ($r = 0.716$; $p<0.001$), while the respective $t_{½}$ values did not ($r = –0.236$). The latter relationship, i.e. between the $t_{½}$ values for VO_2 and HR recorded in the 30-s exercise, are presented in Figure 4 together with the respective mean values (dashed lines). The points in the lower left corner represent subjects, whose rate of recovery was highest (shortest $t_{½}$ values).

Discussion

It seems that physiological processes of recovery, like normalization of heart rate or of oxygen uptake, do not imply their biphasic course of changes. Rather, an attempt was made to explain the observed phenomena from physiological viewpoint. Hence, biphasic courses of changes in those variables are not necessarily a product of specific physiological mechanisms, but may well reflect our habits in interpreting the facts.

Exponential decay curves are most widely used to describe time-related changes in the concentrations of circulating biological substances or their metabolites, and this applies to heart rate or oxygen uptake as well. It may be easily shown that when plotting logarithms of either HR or VO_2 vs. time in order to present the process as exponential, biphasic graphs would be apparent. However, the presumed biphasic course is likely to be an artifact, resulting from the employed co-ordinates (log[variable] vs. time). That view may be supported by the fact that when a simple reciprocal is plotted (1/x vs. x), a biphasic linear course could easily be assumed.

Obviously, the mass action law would not be expected to mechanistically apply to either the post-exercise heart rate or oxygen uptake. Nevertheless, the here presented logit-log plots proved linear, which was indicative of a single-phase process, rather than a biphasic one. In consequence, a single value of half-time enables a simpler description of decreasing EPOC than when used for two phases separately (Åstrand *et al.*

2003). A single-phase presentation would also enable an easy comparison of EPOC courses under various circumstances, like presented in this study for various exercise durations. Obviously, such computed half-time differs from that resulting from a negative exponential equation. In the latter case, every half-time interval reduces the measured variable by half with respect to the previous value while in the logit-log system the consecutive (logarithmic) time intervals double. The logit-log approach thus compensates for the commonly used two- or three-phase models but the half-time, albeit useful in characterizing the post-exercise recovery processes, cannot be considered identical with that obtained from a negative exponential equation.

Two rules should be observed when applying the presented procedure: all values used to compute logits should be net, i.e. the respective resting values subtracted, and zero-time point should correspond to peak value of the given variable (e.g. VO_2, lactate, etc.), otherwise the results would be distorted. Therefore, half-time for given variable is counted from the peak moment of that variable instead of the termination of exercise, but this may apply to submaximal exercises only, as in maximal workouts the peak time coincides with the exercise termination.

No direct comparisons with other reports are possible, since all authors assumed a biphasic course of post-exercise changes, including EPOC (Short and Sedlock 1997). Therefore the comments below may apply to the here presented results only.

As follows from the residual (within-subject) coefficients of correlation presented in Table 2, the $t_{½}$ VO_2 negatively correlated with all other variables; this fact, combined with the fairly high correlation with exercise duration, suggested that the total post-exercise oxygen uptake till $t_{½}$ might be constant. This was indeed confirmed by two-way ANOVA, as no differences between exercises of various durations were found (F<1), and only one subject differed significantly from 9 others, mean oxygen uptakes till $t_{½}$ amounting to 35.1±5.6 and 25.0±3.3 $ml \cdot kg^{-1}$, respectively. Thus, total oxygen uptake from the termination of exercise till $t_{½}$ might represent an interesting characteristic, should it be confirmed in a larger number of subjects and in other forms of exercise.

The presented approach may find useful applications, e.g. in monitoring the progress of training. Athletes, who attain not only highest capacity, e.g. running velocity or power output, at lowest possible physiological cost and are also capable to recover from a maximal (or supramaximal) exertion as fast as possible, are considered the most promising ones. That latter criterion may be easily verified graphically as shown in Figure 4. Namely, subjects recovering fastest from a maximal exercise would exhibit shortest half-recovery times for both HR and oxygen uptake (lower left sector) and those recovering slowly in the upper right sector. Obviously, the application of such criterion would depend on the specificity of given sport and requires that the variables be not correlated significantly with one another, as in this study (Table 2). Such graphs have been successfully used in assessing the performance in multiple, maximal anaerobic exertions (Sienkiewicz-Dianzenza *et al*. 2009, Stupnicki and Sienkiewicz-Dianzenza 2005).

Conclusions

1) Linearity of the logit-log plots for both oxygen uptake and heart rate suggests the use of a single-component model in the post-exercise recovery, which enables characterizing the recovery processes by the half-recovery time.
2) The single-phase pattern of post-exercise recovery processes requires time to be converted to logarithms which compensates for the commonly used two- or three-phase models.
3) Half-recovery time ($t_{½}$) is a reliable index of recovery rate for heart rate or oxygen uptake. The shorter $t_{½}$, the faster the recovery with respect to that variable.
4) The values of half-recovery times for heart rate and oxygen uptake may be used as an efficient tool in monitoring the progress in sport training.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

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