What we may learn from lactate time curves by means of piecewise polynomial regression methods

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ABSTRACT

The piecewise multiphase regression method allows to flexibly combine linear and non-linear functions between a response and a predictor variable in a unique model, respecting the underlying physiology. Routine data of exercise tests of 30 subjects including lactate, heart rate and Borg Scale measurements between 80 and 320 Watt were evaluated by means of multiphase regression models in order to determine deflection points and linearity of curve segments. A two-phase linear-quadratic model was suited to define break points of lactate, heart rate and Borg Scale versus workload curves. Whereas deflection points of the response variables heart and lactate corresponded largely to the aerobic threshold, deflection point of the Borg Scale curve reflected high exercise intensity with lactate levels of about 6 mmol/l, i.e. above the anaerobic threshold. In conclusion, piecewise multiphase regression methods may be suited to improve interpretation of physical exercise tests with regard to lactate, heart rate or even Borg Scales.

Key Words: Lactate, Heart rate, Borg Scale, Exercise test, Piecewise multiphase regression, Deflection points, Variation of lactate levels
INTRODUCTION

Lactate workload curves remain the principle investigation to assess and guide exercise intensity in athletes (1, 2, 3, 4, 5, 6). Moreover, heart rate and subjective perceived exertion (Borg scale) are associated with exercise intensity and may give us basic information about physical performance of subjects (7).

The concept of lactate threshold has been developed in the 1960ies and was primarily promoted by improved laboratory methods which allowed regular capillary blood samples for lactate determinations during exercise tests (8). Interpretation of lactate versus workload curves has unfortunately not been internationally standardized, therefore the definitions given by Binder et al. (3) will be applied in this paper. Briefly, 3 phases (very light exercise, light to moderate exercise and heavy exercise) are separated by two thresholds (TH): 1st lactate threshold (transition of phase I to phase II) corresponding to the “aerobic” TH (Lac ~2 mmol/l) and 2nd lactate threshold (transition between phase II and phase III) corresponding to the “anaerobic” TH (lac ~4 mmol/l). Being aware that the metabolic processes are rather continuous than step-like and thresholds may vary from individual to individual, the first phase is predominantly characterized by oxidative metabolism (fatty acids, glucose via citrate cycle), phase II by an increase of lactate levels due to incremental anaerobic energy supply. However a steady state between production and elimination of lactate can be still maintained. Internationally, the “maximum lactate steady-state” (MLSS) is defined as the highest constant lactate level which can be maintained by the athlete over 30 minutes (8). In this phase II, sometimes called aerobic-anaerobic transition, elimination can still compensate lactate production (9). Finally, in phase III lactate will increase almost exponentially and therefore in athletes this phase will last only for a limited time interval as steady state conditions have been lost.

Heart rate has gained increased importance to control training intensity after inauguration of a standardized Conconi test, which defines the anaerobic threshold based on interruption of the linear heart rate (HR) versus workload (WL) relation, the so-called deflection point (10, 11). With regard to the deflection point, we can approximately suppose the aerobic threshold (Lac ~2 mmol/l) which matches heart rate some 20 bpm lower (12). However, this concept has also been subject of scientific discussion and investigators have to spend much effort for the test (13). In addition, the 15-point (6 to 20) Borg rating of perceived exertion (BS) has gained more interest to measure exercise intensity (3, 7). The Borg Scale or RPE (Rating of Perceived Exertion) corresponds to the subjective perception during physical activity. The reliability of the Borg Scale is acceptable especially for lower intensity, Pearson correlation coefficient r being about 0.8, and decreases to about 0.6 as workload increases (14).
The objective of this study was to assess the piecewise multiphase regression method for analysis of routine effect versus workload curves with regard to performance intensity. The advantage of the method is that deflection points may be determined in an exact and reproducible way.

MATERIAL AND METHODS

30 volunteers underwent a standardized performance test (ergometer: Lode Excalibur Sport; 30 subjects, male students of sports science, aged 20 to 39 years) with simultaneous monitoring of heart rate (HR; Polar HR Monitor) and perceived exertions using the 15-point Borg Scale (BS). The primary purpose of the tests was to assess the performance of the volunteers, and the data were additionally used to prove the principle of the multiphasic regression models for determination of deflection points. All athletes gave their informed consent for retrospective evaluation of the data. All routine exercise tests followed modified standard protocol of the German Association of Sports Medicine. After a brief warm-up and 2-3 minutes of rest, the volunteers started with a workload of 40 Watt and 40 Watt were added every 4 minutes. Capillary blood samples were obtained from ear lobes - a short break was necessary - at rest and the end of each workload level lasting 4 minutes (Accusport Blood Lactate Analyzer). Heart rate was recorded by a 12-lead ECG in upright ergometer position and documented for analysis at the end of each workload level as well. The Borg Scale (Rating Scale of Perceived exertion) was explained to the volunteers prior to the test and assessed synchronously with blood lactate and heart rate. In order to get sufficient data for multiphase model analysis the following workload levels were considered: rest, 80, 120, 160, 200, 240, 280 and – in some cases – 320 Watt. Ergometry was stopped in case of exhaustion or heart rate exceeding 220-age bpm.

All data were evaluated descriptively (mean, standard deviation) and presented by means of appropriate error bar or scatter plots (15, 16). All data were evaluated with commercially available software (NCSS 2007).

Theoretical background of piecewise polynomial regression

The polynomial multiphase method combines several functional relations, which may be linear or nonlinear, into one model (16, 18). In mathematical terms a simple linear-linear-linear model can be written as follows:

\[ Y(x) = A + BX + C(X-D)\text{SIGN}(X-D) + E(X-F)\text{SIGN}(X-F) \]
Three different linear equations are fitted to a specific section of the predictor variable where section borders on the abscissa are specified by \( \text{SIGN}(x-d) \) and \( \text{SIGN}(x-f) \). The sign function defines the specific functional relation with optimal x-values:

\[
\begin{align*}
Y &= a_1 + b_1 \times X & \text{if } x \leq d \\
Y &= a_2 + b_2 \times X & \text{if } d < x \leq f \\
Y &= a_3 + b_3 \times X & \text{if } x > f
\end{align*}
\]

The models also fits the parameters d and f, i.e. provides information about change of phases. The regression segments of the curve may be adjusted by means of suitable non-linear transformations (generally is then given by \( Y = a + b \times X + c \times X^2 \)) to optimize physiological models (note: the term non-linear indicates non-straight lines, which may be linear in strict mathematical terms). However, our purpose was to detect the deflection point where linear relationship between effect and workload skips to non-linear relationship. Linear-quadratic models have proved to be convenient to define this region of transition. The goodness of fit was assessed by means of R-squared, which can be interpreted as the proportion of variance explained by the model (15).

RESULTS

The mean response versus time curves of lactate, heart rate and Borg’s scale are depicted in figures 1 to 3. We find, as expected, smooth increases of the mean values of all characteristics with rising workload, although raw date let suppose some deflections at 120 and 280 Watt with regard to lactate and 80 or 280 Watt with regard to heart rate, respectively. A deflection point of the Borg’s scale versus workload curve may be supposed at a level of 240 Watt. What attracts attention is that the standard deviation of the lactate error bars increase at workload of 120 Watt corresponding to a lactate level of approximately 2 mmol/l, which is in line with the aerobic threshold.
Figure 1: Lactate as a function of workload (mean, SD).

Figure 2: Heart rate as a function of workload (mean, SD).
Figures 3: Borg’s scale sores as a function of workload (mean, SD).

In the next step all response variables underwent piecewise multiphase regression analysis in order to define linear or nonlinear sections (figures 4a-d). The general goodness of fit was entirely satisfactory, R-squared ranging from 0.8 to 0.90 for two-phase piecewise regression models. With regard to three-phase-models, i.e. 3 separate sections of regression, no adequate significant goodness of fit could be achieved.

The lactate versus workload curve deflection point in figure 4a is calculated at 2.67 mmol/l exceeding roughly the theoretical aerobic threshold of 2.0 mmol/l. The approximate aerobic Conconi threshold (fig. 4b) is estimated at about 131.1 bpm (i.e. 151.1-20 bpm), corresponding to a lactate level of 2.26 mmol/l lactate at 137.1 Watt based on the lactate versus workload curve of figure 4a. The latter lactate value is slightly above the deflection point determined by the lactate versus heart curve in figure 4c, being 1.69 mmol/l lactate.

The Borg scale versus workload graph’s deflection point in figure 4d complies more easily with the anaerobic threshold with a workload of 222.8 Watt and can be clearly allocated to phase III of the three-phase model of lactate versus workload curves. The Borg scale deflection point corresponds better to the anaerobic Conconi threshold at 151. bpm. The turn point of the Borg Scale at approximately 16.2 scores or 222.8 Watt corresponds largely to 6 mmol/l lactate of the lactate versus workload curve.
WHAT WE MAY LEARN FROM LACTATE TIME CURVES

Figure 4a: Multiphase linear-quadratic regression model of lactate versus workload. The deflection point was determined at 174.8 Watt or 2.67 mmol/l.

Figure 4b: Multiphase linear-quadratic regression model of heart rate versus workload. The deflection point was determined at 187.1 Watt or 151.9 bpm (anaerobic threshold). The aerobic Conconi threshold would roughly comply with 131.9 bpm or 137.1 Watt and 2.26 mmol lactate, respectively.
Figure 4c: Multiphase linear-quadratic regression model of lactate versus heart rate. The deflection point was determined at 130.1 Watt or 1.69 mmol/l lactate.

Figure 4d: Multiphase linear-quadratic regression model of Borg scale scores versus workload. The deflection point was determined at 222.8 Watt or 16.2 score units.

DISCUSSION

Routine data of 30 male subjects with workloads at rest and between 80 and 320 Watt of ergometry tests were evaluated to prove the principle of piecewise
Multiphase regression models. A two-phase linear-quadratic regression model was able to detect deflection points of lactate, heart rate and Borg scale versus workload curves.

Different approaches have been used to determine break points (turn points, deflection points, transition points) of lactate versus workload curves, which have been improved by log-log transformation of the data (3, 19). A summary of various technical, mostly graphical methods, to stipulate turn points including references can be found under https://de.wikipedia.org/wiki/Anaerobe_Schwelle.20.08.2015.

To date, the SIGN function has not widely been used to determine turn points of lactate versus workload curves, but the method is prima vista suited to separate linear and non-linear sections of such curves (18). The multiphase regression method respects that character of relationship section by section between an y-variable (lactate, heart rate, Borg scale) and an x-variable (workload), although the transitions may be little by little and not abrupt (20). As a proof of principle the method was able to detect turn points of various response versus workload curves. Moreover the method was suited for both linear and non-linear associations depending on the character of the fitted section. In contrast to Binder et al. (3) only a two-phase models could be calculated with sufficient statistical certitude. However, we must take into consideration that routine data were retrospectively evaluated, to show the appropriateness of this new curve fitting approach. The deflections points which could be estimated using lactate or heart rate versus workload curves probably reflect the transition between phase I and phase II of the three-phase lactate model (3). Interestingly, the heart rate (“Conconi approach of aerobic threshold”) fits best with the theoretical lactate break point at 2 mmol/l. The turn point of the Borg Scale at approximately 16.2 scores or 222.8 Watt corresponds largely the anaerobic threshold, although respective lactate levels being slightly higher. This result is in keeping with the result of Scherr et al. (7) and speaks in favor of heavy exercise clearly above the anaerobic threshold in phase III. However, the between-subject variability substantially increases at and after workloads of 120 Watt, which may impede exact determination of deflection points. Probably, analysis of individual data may overcome the interfering influence of variability.

The objective of this first study was to assess the benefit of piecewise multiple regression with regard to performance tests in sports medicine. In general, the data allowed to determine quite reasonable the aerobic threshold using piecewise regression based on the SIGN function. Unfortunately, only 2-section regression models could be calculated, so that a reliable statement about anaerobic threshold is not possible. The deflection of the Borg scale was higher than the expected anaerobic threshold, which may also be due the increasing variability of data above workloads of 120 bpm.
PIECEWISE REGRESSION SUITED TO DETERMINE DEFLECTION POINTS

In conclusion, the piecewise multiphase regression model was suited to discern deflection points of various effect versus workload curves in healthy male subjects during a standard exercise test, especially with regard the aerobic threshold. Further controlled studies are necessary to validate these preliminary results of this section by section approach in physical exercise tests, particularly with regard to the aerobic-anaerobic transition.

REFERENCES


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