Value of the Application of the Heart Rate Performance Curve in Sports

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The heart rate performance curve (HRPC) has been shown to be nonlinearly related to work load. This phenomenon has been used to determine a deflection point and to be related to the lactate anaerobic threshold. The original method was heavily criticized, and the method was challenged by several authors. However, some authors also demonstrated a high value for this method’s application in various sports conditions. Unfortunately, the HRPC was shown to be not uniform and three different patterns were found. Basic investigations have shown a dependence of the HR-deflection on beta1-receptor sensitivity, which gave a plausible explanation of the phenomenon. Important details regarding the testing protocol and the method of turn point determination are given in this review. As a conclusion, we may state that based on numerous studies the method is plausible and valid to determine aerobic exercise performance in various laboratory ergometer and specific sports-related field conditions. Standard protocol conditions adjusted to the exercise performance level of subjects and a computer-supported determination of turn points are necessary to obtain reliable results. Large-scale investigations to validate the heart rate turn point with maximal lactate steady state are still needed. However, from the available literature, the application of this noninvasive method can be recommended to determine aerobic exercise performance in various sports. This noninvasive test is easy to perform repeatedly, which gives interesting possibilities for the monitoring of training adaptation in the short term, such as altitude training or specific taper forms.

Keywords: performance diagnostics, heart rate turn point, lactate turn point, Conconi test

In 1982 the Italian biochemist Francesco Conconi introduced a new method for the noninvasive determination of the anaerobic threshold by means of a simple heart rate performance curve analysis. These authors used the already known phenomenon shown by Brooke and Hamley already in 1972 that the heart rate increase during incremental exercise was found nonlinear with a distinct deflection approaching maximal power output (Figure 1). The deviation from the linear increase at submaximal level, the so-called deflection point was used by Conconi et al to define a marker of aerobic performance, which was shown to be related to
the anaerobic threshold (AT) in their study.\(^1\) However, the method used to determine the AT was not standard, which was discussed critically in the literature.\(^3–5\)

This heart rate (HR)-based method was originally applied to top-level runners but later was expanded to other types of sports such as cycling, cross country skiing, kayaking, and many others.\(^6–10\) The method is very attractive as it is a simple method of applying only heart rate measures using commercially available heart rate monitors.\(^11\)

From the first presentation at the World Congress of Sports Medicine in Vienna, 1982, this method was substantially investigated and critically proven.\(^7\) Besides some enthusiastic articles about this easy method, a great number of critical papers appeared up to the late 1990s.\(^3–5,12–14\) The main critical arguments were as follows:

- No physiological explanation rather than a methodological artifact of the phenomenon\(^15\)
- No causal relationship of the heart rate deflection point and the lactate anaerobic threshold\(^13,14\)
- No standard methods for AT determination were used for comparison by the Italian working group\(^3–5\)
- No uniform time course of the heart rate performance curve and even curves without a deflection at all\(^16–20\)

In 1996 Conconi et al presented an update of the method and gave some comments and results to clarify some of the early questions and criticism.\(^21\) However, there were a substantial number of papers refuting the method.\(^13,14,22,23\) One of the main arguments against the Conconi method was the lack of a physiological explanation of the heart rate deflection phenomenon, although there were several weak points in these papers (eg, no standardized region of interest for the determination of the HRDP using break point regression models, no computer-assisted models of determination of the deflection point, low number of subjects) (Figure 1).
Methodological Considerations

Originally, Conconi et al validated the HR deflection point by using venous blood samples 5 min after single load steps interspersed by 15 min of jogging related to three different intensities above and below the heart rate turn point.\(^1\) The intersection of two straight lines through the first and the second three lactate values obtained was defined as AT which was shown to be significantly related to the running velocity at the deflection point the so-called deflection velocity (vd). This procedure was critically discussed, as there is no standard procedure and there are some pitfalls with this method.\(^2-5\) According to the lactate shuttle theory\(^24-26\) we have to consider a three phase and two turn point behavior of blood lactate concentration\(^18,19,27,28\) and it has to be critically questioned which threshold—the first or the second—has been determined by the Italian group.\(^1,29\) Additionally, Conconi and coworkers never validated their method by means of lactate steady state tests which should be the gold standard for aerobic exercise performance description.\(^30\) These authors also assumed a uniform deflection time course of the HR performance curve and stated that they were able to reduce the unsuccessful tests to near zero.\(^21\) Rather than validate their test by means of standardized laboratory test these authors applied their method to various sports activities in the field such as roller skating, running, cycling, kayaking, rowing.\(^6-10\)

Numerous studies have been published since this first presentation of the method in 1982, but there is still some discussion regarding this method\(^31,32\) although it is widely accepted in the practice in several countries. One main problem is that most studies did not apply an objective computer-supported method to determine the HR deflection point and there are still different approaches concerning the method and the protocol. So, large-scale validation studies using maximal lactate steady state as a gold standard are necessary to clarify the diverse results.

To solve some of these problems of this method, we started to investigate the Conconi method systematically in our working group starting in 1987. The method was especially attractive to apply to children and adolescents\(^6,33-36\) and in situations where invasive techniques are not appropriate such as at working places or in sedentary younger and older subjects.\(^37\) In these investigations we developed a method somewhat different to the method described by Conconi et al with respect to the protocol.\(^1,7\) Different from the original protocol for top-level runners we adapted the method for low-performance subjects tested on cycle ergometer, treadmill and field tests.\(^35\) The main difference was that the original method increased the running speed at fixed distances by reducing running time for this distance whereas we increased power output on the cycle ergometer and later on also on treadmill in fixed and small load steps using also fixed time increments of 60 s, thus avoiding a main criticism raised in the literature.\(^15\) These authors argued that the reduction of time per step in the original protocol will obviously reduce the time for heart rate adaptation to the given load at each step and this will necessarily lead to a deflection of the heart rate performance curve.\(^15\) Later on, Pokan et al investigated this critical point and the authors came to the conclusion that independent of the protocol a deflection could be detected if a true deflection was obtainable in the standard test, demonstrating that a true physiological phenomenon must be the cause for the heart rate deflection and that it is not a methodological artifact.\(^38\)
Physiological Background

From a great number of tests performed in subjects of different performance levels and age there were a number of heart rate curves to be non-regular which was in contrast to Conconi et al.\textsuperscript{1,21} In a study including a great number of young male students we showed three typical patterns of the heart rate performance curve, namely a regular pattern such as described for Conconi’s test, a strictly linear time course without any deflection at all and, even more interesting, an inverted time course of the HRPC in 6–8% of healthy young male subjects without any differences in the lactate performance curve or other related performance variables.\textsuperscript{17} This pattern was also found in master runners\textsuperscript{20} and young healthy female subjects (Figure 2); however, the number of inverted curves was found half of the male counterparts.\textsuperscript{39} This inverted HRPC focused our attention as this pattern was similar to that typically seen in heart disease patients which gave rise to some speculations about pathophysiological (pre)conditions even in young trained and apparently healthy subjects.\textsuperscript{40} One idea was a limit in ventricular function.\textsuperscript{28,40–42} In these studies we found a significant relationship between the degree and the direction of the HRPC deflection and left ventricular ejection fraction (LVEF) measured by means of radionuclide ventriculography (RNV). Further, the turn points for HR and lactate were significantly related to a significant change of LVEF.\textsuperscript{28,41} This relationship was also found in heart disease patients\textsuperscript{40} and was confirmed in trained athletes\textsuperscript{43} and in stable coronary heart disease patients by Foster et al using first-pass radionuclide ventriculography.\textsuperscript{44} Additionally, it was found that oral magnesium supplementation improved both resting and exercise-induced myocardial function in patients with CHD as indicated by the exercise-induced heart rate response.\textsuperscript{45} Foster et al demonstrated these changes in the HRPC and LVEF between pre- and post-percutaneous transluminal coronary angioplasty (PTCA) measures during incremental exercise. The peak heart rate did not change; however, the upward deflection occurred at a higher power output and heart rate and was less after the PTCA intervention.

However, these findings did not explain any causal physiological mechanism and therefore some of the regulatory mechanisms were investigated. Lucia et al (2002)\textsuperscript{47} investigated the relationship of the heart rate deflection to plasma potassium and found a relationship to heart dimensions.\textsuperscript{48} Parasympathetic blockade by atropine did not give any difference in response between subjects with different HRPC response pattern and could not explain the differences in the heart rate response.\textsuperscript{49} The same

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**Figure 2** — Typical examples of the time course of the HR performance curve in young and trained female subjects.
was found for the catecholamine response which was not significantly different between subjects with either regular or inverted HRPC response. As catecholamines have to be related to receptor status, namely, the heart-selective $\beta_1$-adrenoceptor subtype, we further investigated the response of healthy young subjects to a single dose of the $\beta_1$-selective antagonist bisoprolol. This study clearly showed a significant dependence of the response to the antagonist with respect to the different patterns of the HRPC. Regular HRPCs converted to inverted ones using the $\beta_1$-antagonist but inverted HRPCs already under placebo did not change their pattern under $\beta_1$-antagonist application. This clearly pointed out that the inverted HRPC in placebo conditions is caused by a reduced $\beta_1$-receptor sensitivity. So the main cause for the deflection of the HRPC can be seen in the $\beta_1$-receptor sensitivity to the catecholamine response. As the catecholamines also drive muscle metabolism by sympathetic activation, we can assume that the close relationship found between the heart rate deflection point (HRDP) and other threshold values such as the second lactate turn point (LTP$_2$) (Hofmann et al.\cite{17,19,27}) or the second ventilatory turn point (VETP$_2$)\cite{51} is due to the same regulatory mechanisms of the sympathetic drive. One interesting finding was that the pattern was stable in the subjects\cite{52} and could be reproduced several times even when some years have elapsed between tests. This gave rise to speculations about a genetic background of this type of HRPC pattern. In a pilot study in 178 healthy male and female subjects, we investigated a $\beta_1$-adrenoceptor-specific single nucleotide polymorphism. However, this polymorphism did not show any relationship to the degree and the direction of the HRPC in these subjects. In a larger group of the same study population, additional studies on additional SNPs did not show a relationship to the deflection of the HRPC (unpublished results).

**Relationship of HRTP and LTP$_2$, VT$_2$, MLSS**

Irrespective of a physiological explanation several papers have shown that the HRTP was significantly related to other methods of anaerobic threshold determination. There was a good agreement between methods when compared with the second lactate turn point,$^{17,18,27,29}$ the ventilatory turn points,$^{51,54-56}$ and other thresholds such as the EMG threshold$^{27,57,58}$ or the LVEF turn point$^{28}$ applying the same protocol and a uniform computer-supported determination of thresholds. This relationship between different threshold models was also found for patients after myocardial infarction.$^{40}$

This relationship was confirmed by several authors and working groups,$^{59-64}$ however, a great number of authors disagreed and have challenged the HRTP method for several reasons.$^{3-5,13-15,22,23,29,65-68}$

The gold standard for the anaerobic threshold is the so-called maximal lactate steady state during constant load exercise of at least 20 min in duration. The HRTP has also compared with this standard. It was shown that some authors confirmed that the HRTP was able to predict the MLSS for cycle ergometer exercise,$^{27}$ kayaking,$^{69}$ badminton$^{70}$ and even in coronary heart disease patients.$^{71}$ However, other authors have failed to show this relationship.$^3$ Some of the discrepancies may be explained by methodological differences. Figure 3 shows the typical pattern of blood lactate concentration just below and above the HRDP in a trained sports student.$^{57}$

However, evaluation studies in a greater number of subjects are still missing to date. Although there are still some critical concerns about the HRDP method, a number of studies showed that this method may be safely applied and may be valid.
to determine the anaerobic threshold and to predict the MLSS. One limit of the method is that only the second turn point can be determined from the HR response only. To obtain the first turn point equivalent to the first lactate turn point, one needs an additional variable such as the blood lactate concentration or ventilatory variables. One possibility to determine this certain point by heart rate measures only may be the use of the heart rate variability minimum which detects this first turn point consistent with LTP1.

**Application to the Practice**

**General Principles of Testing Protocol to Determine the HRDP**

To avoid the influence of thermoregulation the test duration should be no longer than 12–16 min. The ergometer protocol should be adapted to increase work load by discrete steps and in constant time intervals no longer than 1 min in order to obtain a heart rate performance curve. The first load step should be clearly below the first turn point usually found around 45% of maximal performance or 70% of maximal heart rate. From these assumptions the work load increase may be calculated from the expected maximal performance minus the starting work load divided by 12–16. Usually this gives load increments to increase HR by no more than of 5–7 beats/min independent of exercise performance of the subjects to be tested.

**Specific Principles for Testing in Various Sports**

The same principle as shown above may be applied to different testing situations such as hand crank or rowing ergometer exercise as in these cases it is possible to start with appropriate low exercise intensity, necessary to determine the lower part of the HRPC. A similar approach can be used for walking exercise on a treadmill by increasing the inclination instead of walking speed. Treadmill running is different as it is more difficult to start with a comparably low load for the first load step. However, in trained subjects, a clear S-shaped HRPC can be obtained and the deflection point can be determined easily in cases of a regular HR behavior. Figure 4 shows examples of HRPCs for these different ergometer types. As presented earlier the
second lactate turn point or the second ventilatory turn point were coincident with the HR deflection point in all cases if this heart rate deflection was detectable.\textsuperscript{17,18,51}

**Field Tests**

Applying the method to the field, one has to apply the same general rules as indicated above. On principle, this method can be used in every cyclic sport where it is possible to increase work load from a very low one, below 70% HR\textsubscript{max} up to maximal power output in about 12–16 steps each lasting approximately 1 min. This general principle can be applied to cycling running, cross country skiing, uphill walking, swimming, kayaking, on-water rowing, ice hockey (continuous runs and shuttle runs), tennis, badminton, squash, and even rope skipping exercise for boxers\textsuperscript{7,10,21,59,70,74} The continuous method may be adapted to an intermittent one such as in shuttle runs without or with breaks in-between steps.\textsuperscript{70} In some sports such as in swimming the application of this method maybe limited due to technical reasons although successful tests have been reported.\textsuperscript{74}

Some additional problems may arise in sports such as cycling where it is very difficult to find a safe road to perform tests at a high speed and it seems to be necessary to use a cycling track or to use specific ergometer testing.\textsuperscript{10,21} Tests in cross country skiing are possible on principle;\textsuperscript{75} however, the specific snow conditions, changing sometimes very quickly, make it impossible to compare results. However, for several reasons it makes sense to perform these tests also in varying conditions, but one should respect the limits of field tests. One advantage, however, is that the HR may be stable although conditions vary. This allows the application of HR limits for training even when speed varies with the changes in snow conditions.

This noninvasive test is easy to perform repeatedly within days, which gives interesting possibilities for the monitoring of training adaptation in the short term, such as changes of exercise performance during altitude training\textsuperscript{76} or during specific micro-cycles or the taper phases before competition.

**Conclusions**

Although critically discussed in the past years, one can assume that the heart rate turn point method is based on a plausible explanation, namely, the $\beta_1$-receptor hypothesis. This method was shown to be valid and can be routinely applied.
to the sport practice. However, in some cases, a deflection is not obtainable. Additional large-scale studies regarding the relationship to maximal lactate steady state are required, including subjects of various sports and performance levels. Despite the ongoing scientific debate, this noninvasive test is a useful tool to monitor training-induced changes of endurance performance in athletes and untrained male and female subjects of various age, performance level, and sports participation.

References


