Segmental Trend Lines Define Heart Rate Response to Increased Work

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ABSTRACT

Wyatt FB, Donaldson A. Segmental Trend-Lines Define Heart Rate Response to Increased Work. JEPonline 2013;16(6):59-68. The purpose of this study was to establish mathematical regression trend lines for segmental changes in heart rate (HR) response to increased work in 10 male subjects with a mean (±SD) age of 29.6 ± 8.1 yrs. Pre-exercise testing included height (cm), weight (kg), age (yrs), percent body fat (%), and seated resting HR. The subjects were classified as fit given their mean (±SD) VO2 max of 70.3 ± 6.03 mL·kg⁻¹·min⁻¹. Each subject began the bicycle ergometer test by pedalling at 150 watts (w) of work at a pedal rate of 80 to 90 rev·min⁻¹ for the first 5 min followed by an increase in work of 25 w·min⁻¹ until volitional fatigue. The following measurements were taken during the test: expired ventilation (VE), oxygen consumption (VO₂), carbon dioxide (VCO₂), and HR. Statistical analysis included the descriptive mean (±SD) of subjects and group test results, and the mean (±SD) values across subjects for HR at each measure. Statistical significance was set at P≤0.05. Segments of change for each phase were determined using logarithmic and linear regression analysis of group mean HR. Trend lines of best fit were used for each of the phases. Phase I indicates the withdrawal of the parasympathetic nervous system. Phase II indicates sympathetic influence, and Phase III indicates peripheral afferent signalling. Three phases accompany the subjects' HR response during the incremental bicycle ergometer test. Each phase indicates an established physiological response of the subjects' HR in a sequence of an initial rapid rise, a slower steady rise, and a final rise with a plateau from the onset of exercise to volitional fatigue.

Key Words: Parasympathetic, Sympathetic, Peripheral Afferents
INTRODUCTION

Vagal neural influence on the myocardium is enhanced with fitness level (1,2,4,9). This increase in parasympathetic stimulus results in a reduced resting heart rate (HR) in trained individuals. At the onset of exercise, HR rises dramatically (burst morphology) as a result of parasympathetic withdrawal (5,9,19). This also occurs when blood pH is reduced through hyperventilation or carbon dioxide (CO2) blow-off. Following parasympathetic withdrawal, as workload increases the sympathetic influence on the heart allows for additional increase in HR (1,4,5,8,10,16).

With increasing workloads, a small but discernible breakpoint of HR increase known as the heart rate threshold (HRT) occurs (3,6,7,11,13,17). This point of additional increase in HR has been linked to direct afferent signals emanating from the muscle tissue as a result of metabolite (CO2, H+) accumulation (21,22,36). While the interplay between signals to the heart (i.e., parasympathetic, sympathetic, and metabolite afferent) has been recognized, the characteristic of rate change has not been established. Therefore, the purpose of this study was to establish mathematical regression trend lines for segmental changes in HR response to increased workload.

METHODS

Subjects
Ten males acted as subjects. Each subject was well-trained, given his responses to a health questionnaire and the Par-Q Fitness Readiness Questionaire™. All subjects signed an Informed Consent prior to testing. The research protocol was approved by the Midwestern State University. The following pre-exercise testing measures were taken: height, weight, age, body fat, and seated resting HR (Table 1).

Table 1. Mean (±SD) of Subject Demographics.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>29.6 ± 8.1</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.3 ± 5.1</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>81.4 ± 6.8</td>
</tr>
<tr>
<td>VO2 peak (mL·kg⁻¹·min⁻¹)</td>
<td>70.3 ± 6.03</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>10.5 ± 3.8</td>
</tr>
<tr>
<td>Maximal Power (w)</td>
<td>377.5 ± 23.6</td>
</tr>
<tr>
<td>Maximal Heart Rate (beats·min⁻¹)</td>
<td>187 ± 9</td>
</tr>
</tbody>
</table>

Procedure
After the resting measures were taken, each subject was fitted to the Velotron™ bicycle ergometer. A seated resting HR was taken at this time. The Australian Institute for Sport (AIS) Protocol for the cycle ergometer was utilized for maximal testing purposes. With this protocol, each subject then began the cycle ergometer test by pedaling at 150 watts (w) at a pedal rate between 80 to 90 rev·min⁻¹ for 5 min. After the initial 5 min of pedaling, the workload was increased work at 25 w·min⁻¹ until volitional fatigue.
Measurements
The following measurements were taken with the ParVo Medics™ metabolic system during the cycle ergometer test: beat-by-beat HR (Polar™ RS800CX); expired ventilation (VE), oxygen consumption, (VO2), and carbon dioxide production (VCO2). Upon termination of the test, subjects were allowed a cool-down period before being de-briefed on the results.

Statistics
Statistical analysis included the following: descriptive mean (±SD) of the subjects and group test results. Mean (±SD) values across subjects for HR at each measure (i.e., beat-by-beat). Segments of change for each phase were determined using logarithmic and linear regression analysis of group mean HR. Trend lines of best fit were used for each of the established phases.

RESULTS
Mean HR (beats·min⁻¹) with logarithmic and linear regression lines are presented in Figure 1. The cross-over of these regression lines established the points of phase distinction (2). Phases I, II, and III are presented in Figure 1. Phase I is the parasympathetic withdrawal (via the vagus nerve) with an immediate increase in HR (1,4,5,16,25-27,32 33). Phase II is the sympathetic influence that allows for the increase in HR that matches the increase in workload (1,2,4,5,12,14-16,18,19,22,24,25,27,30,31, 34). Phase III represents the increase in peripheral metabolites, chemoreceptors (i.e., carotid body), and the arterial baroreflex that stimulate the afferent signal increase in HR (3,6-8,10-13,15,21-23,28,29,31,35,36).

![Figure 1. Group Mean Heart Rate Response to Work with Associated Phases.](image-url)

Phase I indicates the withdrawal of the parasympathetic nervous system at the onset of exercise, which was identified with a logarithmic line of best fit (r² = 0.91). Phase II followed, indicating an increase in sympathetic influence on the subjects' HR response. It was identified with a polynomial line of best fit (r² = 0.99). Lastly, the Phase III HR response through peripheral afferents to volitional
fatigue was identified with a 4th order polynomial ($r^2 = 0.99$). All trend lines established for each phase was significantly correlated at $P = 0.001$.

DISCUSSION

From the analysis, it was determined that the three phases accompany the HR response to an incremental workload increase. These phases were determined through a logarithmic/linear regression cross-over technique (35). It has been well-established that the physiological responses of HR follow a sequence of: (a) an initial, rapid rise; (b) a slower, steady rise; and (c) a final rise with a possible plateau from the onset of exercise to volitional fatigue (5,25,27). With the onset of exercise, the primary goal is to rapidly increase HR and VO$_2$ to meet the oxygen needs at the muscle tissue level. The most efficient manner for this goal to be met is with parasympathetic withdrawal and hyperventilation. Therefore, the logarithmic pattern response of HR established the best fit to describe a response characterized by a powerful, rapid rise followed by a leveling off as steady state is reached to signal the transition into Phase II.

Previous studies have categorized the HR response in Phase I as non-linear, curvilinear, and mono-exponential (4,5,9,27). All of these classifications hint at the rapid increase in HR required by the onset of exercise to realize an increase in cardiac output. This study identified the pattern response of group mean HR in Phase I as logarithmic ($r^2 = 0.91$), which was considerably a better fit than a linear trend line ($r^2 = 0.60$). This can be seen in Figure 2. The onset of exercise required an initial rapid rise in HR driven primarily by parasympathetic withdrawal, which was well fit by a logarithmic trend line with its initial rapid rise followed by a slower increase.

In Phase I, trained cyclists have typically demonstrated a rapid response to the onset of exercise that is steeper than an untrained response. Past research findings have noted that endurance trained subjects have faster HR responses at the onset of exercise compared to sedentary subjects (2,20,34). This would lead to a steeper pattern in Phase I due to a more efficient cardiovascular response to the increased energy demand imposed by the onset of exercise.

![Figure 2. Heart Rate Trend Line during Phase I.](image-url)
Therefore, it seems reasonable that a “training” effect is partially responsible for the similar, steeper, logarithmic pattern of HR response produced by the trained cyclists in this study during Phase I. Phase II also showed a similarity of pattern by trend line categorization in which polynomial trend lines showed the highest $r^2$ values for HR response. In Phase II, group mean HR response was best fit with a polynomial trend line. During Phase II, HR began the slower, polynomial rise characteristic of the steady state phase. The powerful and rapid logarithmic response of Phase I as the body transitions from rest to exercise is not needed to meet the demands of the incremental increase in workload during Phase II.

Phase II group mean HR response was best fit by a polynomial trend line ($r^2 = 0.99$). Linear ($r^2 = 0.96$) and exponential ($r^2 = 0.96$) categorizations did not fit the data nearly as well as a polynomial. Phase II HR response can be seen in Figure 3. Previous studies have classified the Phase II HR response primarily as linear (5,27). However, the results of this study indicate that a polynomial trend line should be considered as a viable alternative to the traditional linear classification.

The gradual, upward slope of the Phase II group mean HR response in this study reflected the proportional increase in intensity and in sympathetic activity on the heart (1,4,5,8,10,12,15,16,19,24, 27,29). The group mean Phase III HR response was best fit by a polynomial trend line ($r^2 = 0.99$). Figure 4 indicates the HR response in Phase III.

The final pattern of this response in cyclists has been highly controversial in the literature. Researchers (3) have debated whether a HR deflection or plateau is a normal occurrence with cyclists as they near volitional fatigue. This controversy has led to several classifications of the Phase III response including constant, upward, and downward deflections (3).

In the present study, linear ($r^2 = 0.9937$) and logarithmic ($r^2 = 0.9928$) trend lines were also statistically significant ($P = 0.01$) fit for the group mean. When using a group mean response for a moderately
small sample of cyclists, it is not surprising that a polynomial trend line would be the most appropriate fit in this phase due to the unique physiological response of each cyclist to approaching volitional fatigue. This type of a trend line can accommodate a small group mean average that might contain constant, upward, or downward deflections in pattern that are most prevalent in Phase III. The polynomial pattern response was most certainly a reflection of the many ways that the central command and the exercise pressor reflex can respond to allow for patterned HR responses in spite of impending volitional fatigue (10,12,14,15,19,22,24,25,31).

The combination of central command and the exercise pressor reflex response differed for each of the 10 cyclists as their biological systems attempted to address increasing metabolite concentrations, the inability of the baroreceptor to operate at a higher point, and fatiguing cardiovascular mechanism (28,29,36). In relation to the current study, the Phase III group mean HR response was a steep, rapid rise and ended with a slight downward deflection. This explains why the response was most precisely fit by a polynomial ($r^2 = 0.9941$) trend line while still recognizing the significant linear ($r^2 = 0.9937$) and logarithmic ($r^2 = 0.9928$) trend lines. From this, each segment associated with a distinct trend line establishing the HR change “trend” for that segment.

Moreover, these changes for each stage are physiologically distinct in the following manner: (a) Phase I rate change as a result of parasympathetic neural withdrawal allowing for a rapid increase in HR with an established logarithmic trend line; (b) Phase II rate change as a result of sympathetic neural increase matching workload increase, allowing for a gradual increase in HR response with a 2nd degree polynomial trend line; and (c) Phase III rate change as a result of peripheral metabolite increase with work stimulating a direct afferent signal increasing HR with a 4th degree polynomial trend line.

The findings of similarity in group mean pattern response for cyclists during the AIS test occurred in Phases I and II. In these phases, trend line fitting for each variable led to a similar categorization of the trend line response. In Phase I, HR was best fit by logarithmic trend line, and the ratio comparison of the derivatives of these trend lines produced a constant value. Heart rate was best fit by a 2nd degree polynomial trend line in Phase II. In this phase, the combination of actions by central command and the exercise pressor reflex to maintain HR dynamic constancy were not as rapid and
powerful as Phase I, which was primarily shaped by a strong parasympathetic withdrawal and hyperventilation.

However, Phase II responses showed a similar steady, polynomial increase throughout the phase in response to the increasing workload. In Phase III, HR, which has been shown to deflect or plateau as volitional fatigue approaches, was best fit by a 4th degree polynomial pattern. Thus, this research has established distinct phases of HR response to increased work and provided rate change trend lines for each of these phases.

CONCLUSIONS

Heart rate response during increased work has been shown to follow distinct patterns (5,27). More recent research indicates noted HR variation in response to both steady state conditions and altered intensities of work (2,12,18). In addition, influences on HR variation with exercise show multifaceted signaling patterns from the central nervous system, mechanical properties of the neuromuscular system, and the chemical and flow characteristics of blood (8-10,12,14-16,22,24,28, 36).

The current research identified three phases of response to increasing workloads (Phase I, Phase II, and Phase III). Distinct patterns of HR response were analyzed through regression trend lines with associated physiological influences. This closer analysis of HR response allows for more specific investigations of HR response when comparing groups of different demographics. While the current research utilized a fit population, it is suggested by the investigators that comparisons with different demographic groups (i.e., unfit, pathological) is warranted.

By establishing these patterns and associated physiological influences of HR response with fit samples, noted deviations would allow clinical diagnostics of neurological or metabolic pathologies. Lastly, this research allows for analysis of adaptation responses to training in the athlete. Pre-post testing protocols in athletes would indicate proper adaptations in each phase and the altered physiological mechanisms resulting in part from proper training protocols.

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