Spectral Analysis of Heart Rate Variability during Constant and Pseudorandom Exercise

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The purpose of this study was to investigate the limitation for applying a linear model to the cardiorespiratory control system. Four subjects performed the two types of exercise bouts, constant (CONST) and pseudorandom (PRBS) exercise, on an electrically braked cycle ergometer at three different work rates. The target work rate of CONST were set to 80, 100, 120 % of the individual anaerobic threshold (AT). In PRBS, the work rates were varied between ±10% of the individual AT around the respective target work rates of CONST. Although the spectral density of beat-to-beat heart rate fluctuations showed the conventional patterns for most cases, there was no obvious difference between CONST and PRBS. These results indicated that the variation of ±10% of AT did not affect the heart rate variation as the output response, suggesting a dilemma inevitable to apply a linear model based on the transfer function.

Key word: Spectral analysis, Heart rate variability, Pseudorandom exercise, Anaerobic threshold, Nonlinearity of cardiovascular systems

Heart rate response has been investigated against the various input stimuli during cycle exercise such as sinusoidal, impulse, step, and pseudorandom manners (Wigertz 1970; Casaburi, et al. 1977; Fujiyama, et al. 1973a, b; Greco, et al. 1986). In these researches, linearity of system has usually expected on the physiological mechanisms underlying respiratory and circulatory adjustments to muscular exercise. However, the evidences for nonlinearity of cardiorespiratory control to exercise have also been revealed in some reports (Hughson, et al. 1988; Yamazaki and Sagawa 1989).

In the present study, we reported the case that the spectrum of heart rate fluctuation as an output to the exercise stimuli was not dependent on the input of load such pseudorandom changing, and investigated the limitation for applying the linear model to the cardiorespiratory control system accompanied with exercise.

METHODS

Four subjects were volunteered for this experiments. There age, height, and weight were 26±5 yrs, 173±7 cm, 66±6 kg, respectively. The ventilatory anaerobic threshold (AT) was determined for each subject during a ramp test at the rate of 12 W/min on a cycle ergometer using the conventional criteria (Wasserman, et al. 1973; Caiozzo, et al. 1982; Beaver, et al. 1986).

The subjects performed the constant load exercise following 5 min ramp exercise until the target load (CONST) or the changing load exercise as a pseudorandom binary sequence (PRBS) on an electrically braked cycle ergometer (Ergometer 232C, Combi, Tokyo). In CONST, work rate increased from 0 W to the target value as a ramp manner during 5 min, thereafter the target work rate was maintained during 10 min. The target work rates of CONST were set to 80, 100, 120 % of the individual AT. In PRBS, the work rates were varied
between ± 10% of the individual AT around the respective target work rate of CONST. The unit interval was 1.7 s, and PRBS patterns of 7 bits were generated for four cycles. As the result, total duration of PRBS trials was 14.5 min.

The beat-to-beat instantaneous heart rate was measured with a cardiotachometer (AT-601G, Nihon Kouden, Tokyo), and the output was processed by a personal computer (PC-9801Vm2, NEC, Tokyo). The spectral density as calculated from the consecutive 128 data at the sampling rate of 2 Hz during the constant phase for CONST or the last 3

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**Figure 1.** The amplitude spectral density of heart rate fluctuations during constant exercise at 80% of the individual AT (CONST; right), and pseudorandom binary sequence exercise between 70 and 90% of the individual AT (PRBS; left).
cycles for PRBS trials.

RESULTS

Figure 1 shows the spectral density of heart rate fluctuations for PRBS and CONST. Most of the patterns showed three peaks at the frequencies of less than 0.02 Hz, nearly equal to 0.1 Hz, and more than 0.15 Hz, respectively. Although the higher component was varied with subjects, the lower components less than 0.15 Hz were not affected by the subjects nor the trials. Figure 2 shows heart rate spectra at the higher intensity of exercise than the

110-130%AT
PRBS

120%AT
CONST.

Figure 2. The amplitude spectral density of heart rate fluctuations during constant exercise at 120% of the individual AT (CONST; right), and pseudorandom binary sequence exercise between 110 and 130% of the individual AT (PRBS; left).
individual AT. There was no obvious difference with trials. Comparing with the figure 1, the higher frequency components of heart rate spectra were reduced for all cases. These results indicated that the variation of ±10% of AT did not affect the heart rate variation as the output response.

Figure 3 shows the transition of heart rate spectra for one subject (KT). This did not show the obvious augmentation of the spectral power in PRBS trials. Moreover, the spectral patterns varied with time, especially for the 100% and 120% of AT. These spectral transition could be characterized as the reduction of high frequency components.

**DISCUSSION**

Linear identification of the cardiorespiratory system required an input-output relation which was statistically represented by a transfer function, where the output variability irrelevant to the input was considered to be statistical errors. However, the control of heart rate includes the inherent processes which would express the deterministic fluctuations. We, therefore, compared PRBS with CONST to investigate the effect of changing load on the heart rate variability during exercise. As the results, we obtained the similar spectral patterns of heart rate variability between PRBS and CONST trials.
In general, the components of heart rate spectra were divided between the low and high frequency parts at a border of 0.15 Hz (Akselrod, et al. 1981; Berger, et al. 1989; Saul, et al. 1989), and the higher part was mainly due to the respiratory modulation. If the subject maintained a constant period of respiration, spectral power corresponding with the respiratory frequency would show the prominent peak. On the other hand, the high frequency component would be smoothed if the respiratory frequency varied during exercise. Therefore, the inter-subjects or trials difference of high frequency component could be interpreted as the results of the different respiratory patterns. It indicated that such small variation of exercise loading as in the present study would not affect the heart rate variability. and, therefore, that pseudorandom loading of such a small amplitude as ±10% of the individual AT would not be suitable for the maneuver to analyze the cardiorespiratory control system.

The greater amplitude of PRBS input might show more prominent effects of exercise input on the cardiorespiratory responses. Greco et al. (1986) employed the pseudorandom binary sequence modification to exercise intensity for the identification of the dynamic characteristics of the ventilatory and heart rate responses. Their clear estimates of the impulse responses to exercise would be probably due to the about four times greater amplitudes of PRBS input than in the present study, i.e. 50 % or less of the maximal oxygen uptake versus 20% of the individual AT. It is also, however, the wide agreement that the ventilation and heart rate would not show the linear responses beyond the AT. Therefore, the greater range of the exercise intensity required the more careful consideration to employ the cardiorespiratory systems. Moreover, it was reported that $\dot{V}O_2$ kinetics failed the test of superposition in spite of the intensity below AT (Hughson, et al. 1988). This indicated that there would be no assurance on linearity of the cardiorespiratory systems below AT.

If the linearity of the physiological responses could be applicable to the limited range of exercise intensity, the linear identification of systems could employ for the partial approximation as the maneuver to investigate the physiological control mechanisms. As shown in the present study, however, the output response could not surpass the inherent perturbation of the cardiovascular control systems in the small range of the changing load, where it would be difficult to apply the model of the transfer function. This would be a dilemma which was inevitable to employ a method of linear identification for the analysis of the physiological control systems.

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REFERENCES


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