Heart Rate Response During Exercise and Ventilatory Threshold

1. Introduction

Aerobic exercise is effective in preventing lifestyle-related diseases. In order to make it most effective, the aerobic capacity of each person needs to be assessed periodically to provide them with the best exercise prescription adjusted to them. The maximal oxygen uptake (VO₂max), as an index of aerobic capacity, is considered one of the most reliable indexes of exercise intensity. The VO₂max decreases with age (Buskirk & Hodgson, 1987), and its decrease is recognized as an independent risk factor of cardiovascular diseases (Blair et al., 1995). Therefore, measuring VO₂max is important in maintaining and/or improving the health of the elderly. However, its measurement requires exhaled gas analysis equipment, which is expensive and needs special techniques to use. Also because the
method using VO\textsubscript{2}max requires subjects to perform an incremental exercise up to, or near, the maximum level, its application to the elderly is not easy in terms of safety. Alternative indexes to VO\textsubscript{2}max include the lactate threshold (LT) and the ventilatory threshold (VT) (Mazzeo and Marshall 1991; Beaver et al., 1986). The former is the starting point of a rapid increase in blood lactate against an increase in the exercise intensity during an incremental exercise test; and the latter is the starting point of a rapid increase of CO\textsubscript{2} production (VCO\textsubscript{2}) against an increased O\textsubscript{2} consumption (VO\textsubscript{2}). As the exercise intensities at LT and VT appear near the catecholamine threshold, they are considered the intensities at which the cardiovascular adjustment in the autonomic nervous system shifts from the parasympathetic system to the sympathetic system. Being safe and effective, the exercise intensities at LT and VT are widely used for various purposes including: general fitness of the young and the old, health care of patients, and rehabilitation from heart diseases. The double product (HR × systolic blood pressure) breakpoint (DPBP), at which its value starts accelerating during the incremental exercise, seems correlated to LT and VT, as is suggested in several studies (Tanaka et al., 1997; Riley et al., 1997; Brubaker et al., 1997), which examined healthy people as well as patients, including chronic heart disease. As for the double product in an incremental exercise, it seems to have a close relation with the myocardial oxygen demand (Detry et al., 1970, 1971; Kumahara et al., 2003), and this indicates its credibility of safety as an assessment index. Although safe and realistic due to its not requiring maximum level exercise from the subjects, neither measurement method that uses LT or VT, is applicable yet beyond experimental use, due to specialized equipment and support from experts to use it.

The heart rate (HR) response to incremental exercise usually comes in three phases: Firstly a gradual increase of the HR in low intensity exercise (the 1\textsuperscript{st} phase); acceleration of the HR (the 2\textsuperscript{nd} phase); a decrease in the degree of the HR increase in high intensity exercise (the 3\textsuperscript{rd} phase) (Brooke & Hamley 1972). As for the HR response in the transition from the 2\textsuperscript{nd} to the 3\textsuperscript{rd} phase, its similarity to the HR response at LT is reported in Conconi et al. (1982). Hofmann et al. (1997) suggests, however, a possibility of its reflecting the 2\textsuperscript{nd} transitional point of lactic acid or the onset of blood lactate rather than LT. Tanaka et al. (1997), comparing changes of the HR against exercise intensity before and after LT, reports an increase of HR at the intensity above the LT level. These results suggest an association between the transitional period from the 1\textsuperscript{st} to the 2\textsuperscript{nd} phase and LT. Also, from the close relation between DPBP and LT, it can be assumed that the change in the HR from the 1\textsuperscript{st} to the 2\textsuperscript{nd} phase, too, correlates to LT. Thus, it is a possibility that the HR response during incremental exercise can be used as a simple, safe, and economic measurement index of aerobic capacity.

We defined the change in the HR during the 1\textsuperscript{st} to the 2\textsuperscript{nd} phase transition during the incremental exercise test as HR break point (HRBP). In the present study, in order to determine the reliability of HRBP as an index of aerobic capacity, we compared correlation of HRBP with VT to that of DPBP with VT.

2. Methods

2.1. Subjects

The subjects in Experiment 1 are composed of 97 middle-aged and elderly adults, 52-79 years old (32 males and 65 females), who have no apparent cardiac diseases. The subjects in Experiment 2 are eight elderly people, 70-76 years old (four males and four females). The characteristics of the subjects of each experiment are shown in Table 1. All subjects gave their written informed consent to participate. This study was reviewed and approved by the local Institutional Review Board.

2.2. Exercise test

An incremental exercise test was conducted using a bicycle ergometer (232 CXL, Combi Wellness, Tokyo), on the subjects after they took a rest. The subjects firstly performed four minutes warm-up with an exercise intensity of 20 watts, and continued the ramp-style incremental exercise at 10 watts/min until they felt exhausted or reached 85% of the age-predicted maximum HR (220 – age) or 250 mmHg of systolic blood pressure. In Experiment 2, the ramp incremental exercise tests were conducted twice on two separate days by limiting the HR reserve at 75%.
2.3. Ventilatory threshold (VT)

VO\textsubscript{2} and VCO\textsubscript{2} during the rest and the incremental exercise were recorded continually breath-by-breath with an Aeromonitor AE-300 (Minato Ikagaku, Tokyo). For both VO\textsubscript{2} and VCO\textsubscript{2}, the mean value was calculated every 15 seconds. Three researchers who are well versed in the area determined VT using the V-slope method (Beaver et al., 1986) and the mean value of VT determined by three researchers was obtained.

2.4. Determination DPBP and HRBP

Arterial blood waveforms were continually recorded from two minutes before the exercise throughout the incremental exercise by using the Volume-clamp method, with the cuff of a continuous finger blood pressure measurement device (Portapress, TNO-TPD Biomedical Instrumentation, Amsterdam) wound around the middle finger of the right hand of the subject.

After that, by using hemodynamic analysis software (Beat Scope, TNO-TPD Biomedical Instrumentation, Amsterdam), blood pressure and HR were calculated beat-to-beat, and then each mean value of blood pressure and HR, each, was calculated every five seconds. In determining DPBP and HRBP, the linear regression line between the work rate and the double product or HR was drawn by moving through slat points, and then the point where the slope of the two regression lines (2\textsuperscript{nd} line: 1\textsuperscript{st} line) was the largest was automatically decided as DPBP and HRBP, respectively. In case some obvious data deviation was confirmed and the mechanically determined DPBP was considered inappropriate, the breakpoint was re-determined after removing the outliers. Researchers who decided DPBP and HRBP were set different from those who determined VT.

2.5. Metabolic equivalents (METs)

Metabolic equivalents (METs) were calculated, based on the work rates at VT, DPBP and HRBP, each, in the following equations:

\begin{equation}
1 \text{ watt} = 1 \text{ J/s} = 0.014334 \text{ kcal/min}
\end{equation}

\begin{equation}
1 \text{ℓ} \text{ O}_2 = 5 \text{ kcal}
\end{equation}

\begin{equation}
1 \text{ MET} = 3.5 \text { ml/kg/min} = 0.0175 \text{ kcal}/\text{body weight}
\end{equation}

From the above equations (1) to (3) and the energy efficiency rate of the aerobike 0.232, the following equations were drawn:

\begin{equation}
\text{METs} = \frac{\text{watts}}{1.22 \times 0.232 \times \text{body weight}}
\end{equation}

\begin{equation}
\text{METs} = \frac{\text{watts}}{0.283 \times \text{body weight}}
\end{equation}

2.6. Statistics

By using the breakpoint, detected at the time DPBP/HRBP were determined, the slopes of the two regression lines, formed by bending them at the breakpoint, were calculated and compared by a paired \( t \)-test. Work rate, METs, and HR at VT, DPBP, and HRBP were compared by repeated-measures ANOVA. In case the F value was significant, multiple comparisons were conducted by further applying the Newman-Keuls method. The single
correlation coefficients were calculated between variables of interest. The agreement between the two variables was assessed with the Bland and Altman plot. Also, two correlation coefficients were compared by applying the \( z \)-conversion of Fischer’ correlation coefficient. \( P < 0.05 \) was accepted as significant.

### 3. Results

#### 3.1. Experiment 1

VT was determined for all subjects by V-slope method. \( \dot{V}O_2 \) at VT was 13.7±2.5 ml/kg/min. DPBP and HRBP were also determined for all subjects. Figure 1 shows an example of the double product and HR response during incremental exercise. Comparison of the slopes of the regression lines between the work rate and the double product before and after DPBP indicated that the slope after DPBP was significantly larger than that before DPBP (1.1±0.8 vs. 3.3±1.4 ×10\(^2\)/watt, \( P < 0.0001 \)). In the same way, comparison of the slopes of the regression lines between the work rate and the HR before and after HRBP showed that the slope after HRBP was significantly bigger than that before HRBP (0.5±0.4 bpm/watt, \( P < 0.0001 \)).

Table 2 shows the work rate, METs, and HR at VT, DPBP, and HRBP. There were no significant differences in work rate or METs between VT and DPBP/HRBP. However, the HR both at DPBP and HRBP were significantly lower than that at VT (both \( P < 0.05 \)).

As shown in Figure 2, correlations between the work rate at VT and that at DPBP/HRBP were significant (\( r = 0.873 \) and \( r = 0.773, P < 0.0001 \) for both). The correlation coefficient with the work rate at VT was significantly larger in DPBP than in HRBP (\( p < 0.05 \)). Average error was 0.8±6.6watts for the former, and 0.2±8.8watts for the latter, indicating no significant differences between them. Correlations between METs at VT and that at DPBP/HRBP were also significant (\( r = 0.881 \) and \( r = 0.797, P < 0.0001 \) for both, Figure 3). The correlation coefficient with METs at VT was significantly larger in DPBP than in HRBP (\( \rho < 0.05 \)). Average error was -0.05±0.4 METs for the former, and 0.02±0.6METs for the latter, indicating no significant differences between them. Correlations between HR at VT and that at DPBP/HRBP were significant (\( r = 0.905 \) and \( r = 0.857, P < 0.0001 \) for both, Figure 4), and no significant differences were shown between the HR at DPBP and those at HRBP. Average errors were -2.6±6.1 bpm for the former, and -1.6±7.3 bpm for the latter, indicating no significant differences between them.

#### 3.2. Experiment 2

Excellent reproducibility was observed in the work rate, METs, and HR at HRBP (\( r = 0.836–0.919, \)
HRBP showed a good reproducibility, with the variation coefficient of the work rate at HRBP 8.7%, and that of the HR at HRBP 3.3%, even though the small number of subjects. These results suggest that the exercise load and the HR at HRBP can be useful indexes to prescribe training intensity for the middle-aged and elderly.

HRBP seems to be associated with the following physiological phenomena: The cardiac output increases in linear proportion to an increase in exercise intensity. While the stroke volume and the HR, deciding factors of the cardiac output, increases in linear proportion up to near 40% VO2 max, after that the stroke volume comes to the plateau or starts decreasing, except for endurance-trained athletes (Zhou et al., 2001; Powers et al., 1993; Gledhill et al., 1994; Astrand et al., 1964; Fleg et al., 1994; and Seals et al. 1994). Generally, the HR seems to be increased to cope with the demand of cardiac output. An increase in the HR is considered affected by the following factors: the HR decreases during the rest or low intensity exercise period due to the functions of the parasympathetic nervous system; and the HR increases during exercises of middle and above intensity, when the sympathetic nervous system is activated (Nakamura et al. 1993; Saito et al. 1993; Saito and Nakamura 1995). Plasma catecholamine,
Figure 3  Correlations between METs at VT and that at DPBP (above) and at HRBP (below): Expressed by scatter diagram (Left) and Bland and Altman's Plot (Right).

Figure 4  Correlations between the heart rate at VT and that at DPBP (above) and at HRBP (below): Expressed by scatter diagram (Left) and Bland and Altman's Plot (Right).
an index of sympathetic nervous system activity, is maintained at the level of the rest period during a low intensity exercise, and then rapidly increases with the increasing of exercise intensity. Along with this increase, blood lactate level, pulmonary ventilation, and the double product start increasing rapidly (Mazzeo and Marshall, 1991; Beaver et al., 1986; and Tanaka et al., 1997). Such changes in plasma catecholamine level caused by exercise intensity closely relate to the appearances of LT, VT and DPBP. HRBP, along with these variables, too, seems related to an increase in sympathetic nervous system activity.

Tanaka et al. (1997) compared the regression line between the VO\textsubscript{2} and the double product during incremental exercise between before and after LT and indicated that the slope after LT was larger than before LT. As for the slopes of the regression line between VO\textsubscript{2} and HR, Tanaka et al. (1997) indicated that they are either unchanged before and after LT, or in 25% of the cases even become smaller after LT appeared. Although this is indicating a less clear nature of detecting HRBP than DPBP, this study could confirm HRBP for all of the total 113 subjects. The ratio of increase in the HR against that of the work rate is significantly larger after HRBP than before HRBP, as much as two times on average. On the other hand, the ratio of increase in the double product against that of the work rate after DPBP is about three times larger on average than before DPBP. The finding that HRBP is smaller than DPBP in the change in the slopes between before and after the breakpoint may indicate the difficulty involved in determining the breakpoint. However, by applying a mathematical method, the HR alone may be enough to determine the breakpoint of the increase in the HR against that of the work rate. The higher rate of HRBP in the present study seems to be affected by several factors, including the following: Firstly, whereas previous studies covered subjects ranging from the young to the elderly, this study narrowed its focus on the middle-aged and the elderly. Plasma level of catecholamine against the same exercise intensity is higher in the elderly than in the young (Fleg et al., 1985). On the other hand, aging causes a decline in β-adrenoceptive sensitivity, and the HR of the elderly responding to the same amount of injected catecholamine becomes smaller (Vestal et al., 1979; and Fleisch, 1980). These findings make it difficult to reach a simple conclusion on the effects of the speed of HR increase and β-adrenalin response by age. However, it is confirmed that thickening walls of the blood vessels and their narrowed inside due to aging causes an increase of blood pressure response against a given α-sympathetic nervous activation. The rise of blood pressure speed against an incremental workload triggers a positive feedback as a response. This is an activation of the sympathetic nervous system that causes an increase in the HR rising speed. Another reason for the higher HRBP detection probability in this study may be that whereas the incremental exercise tests in previous studies were terminated at the subject’s exhaustion point, this study set the termination point at the 85% of the age-predicted maximum HR. The HR during an incremental exercise test usually shifts in three stages: it slowly rises against a low intensity exercise (the 1\textsuperscript{st} phase); it accelerates (the 2\textsuperscript{nd} phase), and then the increase declines against a high intensity exercise (the 3\textsuperscript{rd} phase) (Brooke and Hamley, 1972). As for the HR in the 3\textsuperscript{rd} phase, there are reports suggesting a further rise of the HR in the 3\textsuperscript{rd} phase as in Conconi et al. (1982). Aside from the HR either increasing or decreasing in the 3\textsuperscript{rd} phase, inclusion of the HR during high intensity exercise in the data seems likely to cause errors in the determined value of HRBP. Particularly, in cases where the data include the growing rate of the HR response becoming smaller, the slopes of the regression lines between the oxygen uptake and the HR may become smaller at the exercise intensity of LT and above, as reported in Tanaka et al. (1997). Because HRBP in this study was decided after the HR during high intensity exercise was removed from the data, the change in the HR from the 1\textsuperscript{st} to the 2\textsuperscript{nd} phase seems to have been more correctly assessed. The third reason for the higher detection probability of HRBP in this study may reside in the difference of the capacity of time resolution used for the measurement of the double product and the HR. In the previous study in Tanaka et al. (1997), systolic blood pressure was measured by the oscillometric method, which requires a minimum 15 sec. sampling interval, and the HR breakpoint was also analyzed by using the same time-resolution. This study, however, continuously recorded the finger arterial blood pressure waveform with the Volume-clamp method, and gained the mean value of the double product and the HR, each, every 5 seconds, through the analysis of the waveforms. Such difference in time-resolution
will affect the precision of HRBP detection in cases where difference in the slopes of the regression lines between the work rate and the HR before and after HRBP is small, or when a HR increase against the steady increase of the work rate is small.

Errors in the work rate, METs and the HR between at VT and DPBP are -0.8±6.6 watts, -0.05±0.4 METs and -2.6±6.1 bpm, respectively. Errors in those at VT and HRBP are 0.2±8.8 watts, 0.02±0.6 METs and -1.6±7.3 bpm. In all the errors, there were no significant differences between DPBP and HRBP. This suggests the possibility of HRBP appearing at almost the same exercise intensity with VT, as in the case of DPBP. Assessment of the exercise intensity by METs, which is a commonly used method in actual exercise prescription, indicates that errors from METs at VT, which are ±2SD, are within the ±1 METs range for both DPBP and HRBP. These errors may be within an allowable range. The recommendation from the Centers for Disease Control and Prevention and American College of Sports Medicine stated that individuals should engage physical activity at a relative intensity of 40% to 60% of VO\textsubscript{2}\text{max} or absolute intensity of 4 to 6 METs for prevention of cardiovascular diseases (Pate et al., 1995; Pearson et al., 2002). This indicates that prescribed exercise intensities are usually expressed with some range of allowance. The errors shown above will be within an allowable range. The rate of perceived exertion at a given same exercise intensity may change due to the person’s health condition of the day and other factors. So, it will be desirable to keep some allowance in exercise prescription, so that each individual can adjust the load to suit his/her health condition. In cases where the errors from the workload at VT exceeded the ±2SD allowable range, as in four cases with DPBP and six with HRBP, each case will need more detailed examination, including the possibilities where the source of the problem resides in the determined values of DPBP, HRBP, or even VT itself.

The use of HRBP can be concluded as a safe and inexpensive method for the assessment of aerobic capacity, but its safe and effective use without the supervision of an expert will need to be further addressed.

5. Conclusion

The results of the present study suggest that the work rate or the HR at HRBP can be used as an indicator of aerobic exercise intensity for the middle-aged and the elderly.

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Hofmann P., Pokan R., von Duvillard S. P., Seibert F. J., Zwieker...
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Name:
Jun Sugawara

Affiliation:
Institute for Human Science and Biomedical Engineering, National Institute of Advanced Industrial Science and Technology, Tsukuba

Address:
1-1-1 Higashi, Tsukuba, Ibaraki 305-8566 Japan

Brief Biographical History:
1997- Doctoral program in Health and Sport Sciences, University of Tsukuba.
2000- Centre for Tsukuba Advanced Research Alliance, University of Tsukuba.
2002- Institute for Human Science and Biomedical Engineering, National Institute of Advanced Industrial Science and Technology (AIST)

Main Works:
• Brachial-Ankle Pulse Wave Velocity: An Index of Central Arterial Stiffness? J Human Hypertension. 19: 401-406, 2005

Membership in Learned Societies:
• Japan Society of Physical Education, Health and Sport Sciences
• American College of Sports Medicine (ACSM)
• American Heart Association (AHA)