Time constant of heart rate recovery after low level exercise as a useful measure of cardiovascular fitness

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Abstract— In this study we aimed to establish the usefulness of the time constant of heart rate recovery (Tr) in the evaluation of cardiovascular fitness. 15 male subjects exercised on recumbent bicycle at three different workloads (75W, 100W 125W) where R-R intervals were monitored to determine Tr. In order to find the maximal oxygen uptake ($\dot{V}O_{2\max}$) of each subject, oxygen consumption rate ($\dot{V}O_2$) was recorded throughout the treadmill exercise (10km/h). Based on $\dot{V}O_{2\max}$, we classified the subjects into two groups: the "fit" group and the "unfit" group. We found a significant difference in Tr between these two groups only existed when the workload was 75W (p ≤ 0.01) and only at this workload did the R-R intervals achieve stability during the 5 minutes of exercise. Furthermore, we found the cut-off value for predicting cardiovascular fitness at this workload was 55 seconds, with an associated sensitivity of 85.7% and specificity of 87.5%.

I. INTRODUCTION

As maximal oxygen uptake ($\dot{V}O_{2\max}$) is an indirect estimate of maximal cardiac output [1] [2], it is considered to be the most reliable index of cardiovascular fitness. The index is defined as the point at which oxygen uptake ($\dot{V}O_2$) reaches a plateau despite further increases in the work rate. However, a true plateau in $\dot{V}O_2$ cannot always be attained during standard incremental exercise [3] [4]. And also, it is well known that the value of $\dot{V}O_{2\max}$ depends on the measurement method, for instance, bicycle exercise induces a smaller value for $\dot{V}O_{2\max}$ [5]. Therefore, $\dot{V}O_{2\max}$ may not be the best index of cardiovascular fitness.

Heart rate (HR) responses after exercise appear to be an important component in the assessment of cardiovascular health. During exercise, a combination of parasympathetic withdrawal and sympathetic activation leads to an increase of heart rate to satisfy energy demands of the working muscles [6]. Both somatic exercise reflexes and central command mechanisms mediate those autonomic changes. In contrast, the rapid decline in heart rate after the cessation of exercise is theorized to be due to high vagal tone associated with both the cardiorespiratory fitness level of the individual and the intensity of exercise [7]. Studies have shown that heart rate recovery is faster in trained subjects than in untrained subjects [8] [9] [10] and is moderately related (r = -0.75; p< 0.05) to $\dot{V}O_{2\max}$ [11].

Although earlier physiological studies suggested a rapid HR recovery rate after relatively high levels of exercise, is a marker of physical fitness, the usefulness of this variable has not been generally discussed. Studies demonstrate that HR declines monoexponentially after exercise [12] [13]. It has also been suggested that the time constant of heart rate decay for 5 minutes after exercise depends on both rapid vagal reactivation and gradual sympathetic withdrawal [14]. Consequently, the time constants of the heart rate decay may predominantly reflect cardiovascular fitness.

In this study, a practical and relatively easy method has been proposed to assess cardiovascular fitness between individuals. A suitable low intensity and short duration exercise was chosen for the test and the time constants of heart rate decay after the exercise (Tr) was studied. Furthermore, a cut-off point for Tr was developed to characterize a subject's fitness.

II. METHODS

A. Subjects

The study was performed on 15 healthy untrained male volunteers aged (mean ± RMS) 34 ± 1.5 years, body weight: 71.5 ± 6.5kg, height: 171.0 ± 6.6 cm. None of the subjects were taking any medicine known to affect cardiovascular function and all of them were asked to avoid smoking and drinking alcoholic beverages before the experiments.

B. Procedures

The experimental protocol consisted of two sessions conducted on separate days.

Session 1: On the first day the maximal rate of oxygen uptake ($\dot{V}O_{2\max}$) was determined for each subject to assess their level of cardiovascular fitness. To determine $\dot{V}O_{2\max}$, a submaximal prediction procedure proposed by Astrand and Rhyming [15] was used. All subjects performed the test on a computer controlled treadmill running at a speed of 10km/h for 5 minutes. HR and the pulmonary gas exchange were measured during the last two minutes of the test in order to

calculate the heart rate and oxygen intake for this submaximal exercise. From this we computed the $\dot{V}O_{2\,max}$ by using the heart rate and relative oxygen intake based on Astrand and Rhyming method.

Session 2. Participants were asked to have a complete rest for some time before exercising on a bicycle (Tunturi Exercise Cycle E6). The beat by beat heart rate was measured in three stages: first a measurements is taken one minute before exercise to establish the resting HR. It was then recorded continuously during five minutes of exercise, and finally for 5 minutes after the cessation of exercise to track the recovery phase.

The above procedure was performed on each subject at three different levels of workload set at 75W, 100W and 125W. Each subject was asked to carry out this same sequence three times on different days.

III. INSTRUMENTATION

During the first session, the gas exchange was measured using a Han-Rudolph Model 6900series mouthpiece valve and nose clip. Minute ventilation was measured during inspiration using a Flow Transducer model K520-C521 (Applied Electrochemistry, USA). Expired gas concentrations of oxygen and carbon dioxide were analyzed from a 4.2-L mixing chamber using Applied Electrochemistry S-3A and CD-3A gas analyzers. The outputs of both flow transducer and the gas analyzers were interfaced to a laptop through an A/D converter (National Instruments DAQ 6062E in 12 bits resolution) with a sampling rate of 200 Hz. Programs were developed in Labview 7.0 to calculate and record the oxygen consumption rate.

During both sessions (session 1 and session 2) the heart rate, represented by its reciprocal value, the RR interval in seconds, was monitored beat by beat using a single lead ECG device with a sampling rate of 500Hz.

IV. DATA REDUCTIONS

Throughout the registration period (session 2), there were considerable beat by beat variations which were not related to exercise. They were partly removed by calculating the average response from three identical experiments in each subject at the same workload. Because the original sampling was in discrete heartbeats of variable duration, all recorded variables were converted into 5 Hz sampled by spline interpolation. The averaged response was then calculated as the mean of each set of synchronous samples for each 5 Hz time step. To further eliminate any non-relevant high frequency variations present in RR intervals, the individual averaged curves were low-pass filtered. All the individual averaged curves were then pooled to establish the inter-individual averaged responses by finding the mean value in each set of synchronous samples from 15 recordings. Figure 1 shows the above data processing method.
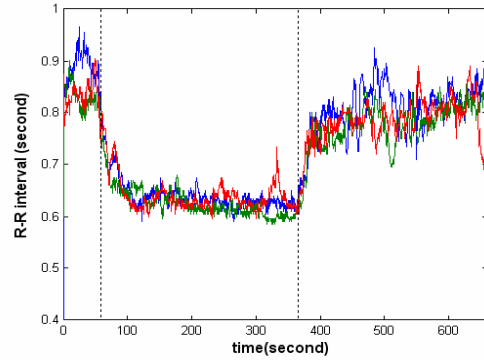
(a). Results of three identical experiments with the same subject (workload = 75W).
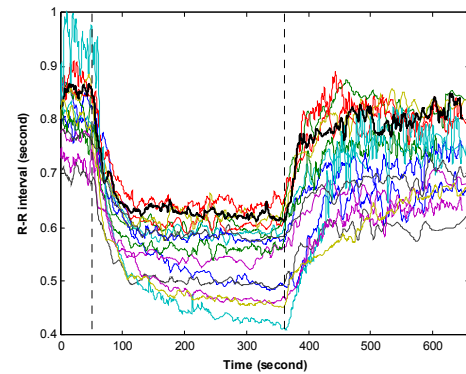
(b). Averaged response (bold line) computed from experiments (a) above and for other 14 subjects (workload =75W).
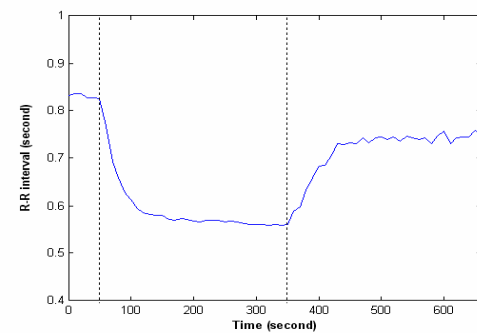
(c) Mean of the responses from 15 recordings in (b) above.

Figure 1. Averaging for same subject and averaging between subjects (workload = 75W). First vertical dotted line is the start of exercise and the second dotted line is the end of exercise.
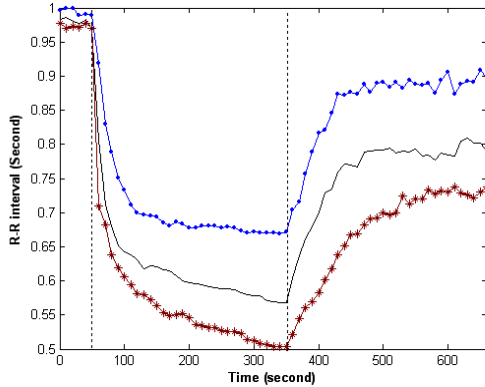
Fig 2. Mean value of the normalised response at three levels of workload. The point line is for 75W, the solid line is for 100W and the asterisk line is for 125W. First vertical dotted line is the start of exercise and the second dotted line is the end of exercise

V. RESULTS

By using the mean of the normalized method shown in figure 1, we calculate the mean values of the normalized response for 15 recordings at three different levels of workload in Figure 2. From this figure, the well-known very rapid decrease in RR intervals at the onset of exercise was seen as expected. The exercise pattern was characterized by a rapid decrease in RR interval followed by a progressively slower decline. We also found that during the 5 minutes of exercise, the RR intervals achieved stability in the last two or three minutes when the workload is 75W. This indicates that the cardiovascular system in general can tolerate this exercise level (75W) and that this exercise level is within the aerobic exercise limitation for most people. However for the workload of 100W and 125W, the RR intervals behaved differently, decreasing during the whole stage of exercise.

These data suggest that a workload of 75W is a suitable exercise level for cardiovascular testing. After the cessation of exercise, the RR interval rapidly increases for the first one to two minutes and then rises gradually. Indeed, a significant time period is required before the RR interval returns to resting levels. Even for moderate exercise, the RR interval remains elevated below the pre-exercise level for a relative long period of time (up to 60 min)[1]. Figure 2 also demonstrates that the RR interval increase mono-exponentially after exercise. Similar results were observed in previous studies [7] [8].

In this study, we used Tr (the time constant after the cessation of exercise) as an index to assess the subject's cardiovascular fitness. Tr was calculated from a dynamic analysis of the increase in the RR intervals by adopting the following equation.

$$RR(t) = b_0 - a_0 e^{(-t/T)}$$

where t is the time from the cessation of exercise, b_0 is asymptotic value of RR interval for t $= \infty$, a_0 is the increment from the start of exercise to the end of exercise for t $= \infty$, and T is the time constant.

We calculated Tr at each of the three levels of workload (75W, 100W, 125W) for all of the subjects. For descriptive purposes, the subjects were classified into two groups on the basis of the value of their $\dot{V}O_{2\,max}$ [16] (calculated from session 1). The two groups are described as the "fit group" and the "unfit group". For each of the levels of exercise, Tr differences between groups were compared by using Wilcoxon rank-sum test. An alpha level of p $\leq$ 0.01 was used to establish significance.

Based on the establish significance where p $\leq$ 0.01, the statistical results show that a significant difference between Tr in the two groups only exists at the workload of 75W (p $\leq$ 0.01). There is no significant difference for the other two workloads (100W and 125W). Consequently, the Tr at the workload of 75W was selected as the index to assess cardiovascular fitness. Table 1 gives the Tr for the two groups at the workload of 75W. Also, Figure 3 gives the scattergram relating the reciprocal of Tr at the workload of 75W to $\dot{V}O_{2\,max}$ which are estimated using Astrand and Rhyming method for all the 15 subjects. It shows that the reciprocal of Tr is related to $\dot{V}O_{2\,max}$ with r =0.8126. It also demonstrates that with the increase of $\dot{V}O_{2\,max}$ the corresponding Tr is decrease.

A value of Tr which provides the best discrimination between the fit and the unfit group was determined by examining the trade off between sensitivity and specificity in the Receiver Operating Characteristic (ROC) curve for all possible cut-off points; this cut-off point turns out to be 55 seconds. And the sensitivity and specificity values of the abnormal Tr for prediction of unfitness were 85.7% and 87.5%, respectively.

VI. CONCLUSION

The results of this study indicate that even simple exercise can provide information about an individual's cardiovascular fitness. We selected the recumbent bicycle, a workload of 75W, an exercise duration is 5 minute and Tr is the index for predicting individual cardiovascular fitness. There are two reasons for using this method. The first is that HR can achieve stability during the last two or three minutes of exercise only when the workload is $\leq$ 75W. The second is that in terms of Tr, significant difference between groups only exists at workload of 75W (p = 0.0059). Furthermore, we found the cut-off value for predicting cardiovascular fitness at this workload was 55 seconds.

In summary, this study reveals the possibility that cardiovascular fitness can be established by using the result of low intensity and short duration exercise. This provides a

valuable means of assessing the cardiovascular fitness for those unable to undertake more complex and demanding tests, such as the elderly or people with heart or respiratory disease.

TABLE I
TIME CONSTANT FOR THE RECOVERY FROM EXERCISE
(WORKLOAD = 75W)

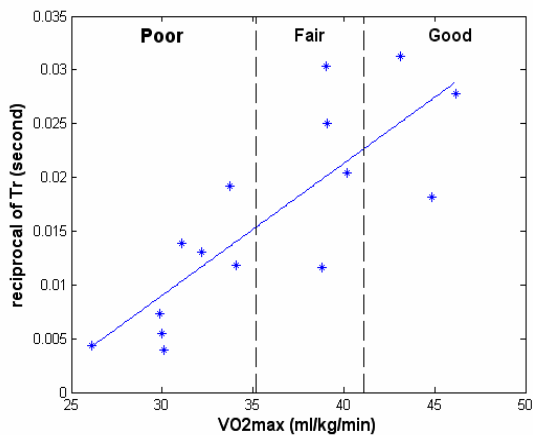| Tr for fit group (second)	Tr for unfit group (second)
49	52
40	258
36	72
55	228
33	77
32	182
86	85
	137
mean ± SD	mean ± SD
47.29 ± 19.06	136.38 ± 78.10

Fig. 3. Scattergram relating reciprocal of Tr at the workload of 75W to $\dot{V}O_{2\max}$ estimated using Astrand and Rhyming method for the 15 subjects. The dotted line separates the fitness classifications on the value of $\dot{V}O_{2\max}$ basis. The three fitness classifications are poor, fair and good as shown in the figure.

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