Heart Rate Recovery After Exercise: A Study by Wavelet Analysis

LR Davrath[1], I Pinhas[1], A Beck[1], M Scheinowitz[1, 2], D Elian[2, 3], S Akselrod[1]

[1]Tel Aviv University, Tel Aviv; [2]Procardia-Cardiostyle Maccabi Health Insurance, Tel Aviv; [3]Sheba Medical Center, Tel Hashomer, Israel

Abstract

The reduction in heart rate (HR) during the first min of recovery immediately after a maximal exercise stress test (GXT) has recently been found to be a powerful and independent predictor of mortality. A modified Continuous Wavelet Transform (CWT) designed in our lab, is used to perform time-dependent spectral analysis during the non steady-state conditions created by GXT. This method provides dynamic measures of the low frequency (LF) and high frequency (HF) peaks, associated with autonomic activity. A group of 18 patients underwent GXT using the Bruce Protocol. Five of 18 patients demonstrated pathologic delta HR ($\leq$18 bpm), while 13 patients displayed normal delta HR (>18 bpm). Patients with pathologic delta HR displayed significantly ($p<0.05$) lower HF fluctuations at one-min post exercise than did the controls. Attenuated delta HR upon recovery from GXT is indeed associated with abnormal vagal function, as assessed by CWT.

1. Introduction

The reduction in heart rate (HR) during the first minute of recovery immediately after a maximal exercise stress test (GXT) has recently been found to be a powerful and independent predictor for cardiovascular mortality [1-3]. Heart rate recovery was defined as the difference in heart rate between peak exercise and one-minute post exercise. In this study, a value of $\leq$18 bpm is defined as pathologic delta HR. It is currently assumed that a pathologic delta HR after exercise is associated with reduced parasympathetic activity [1], yet this has not been proven.

Examination of autonomic control during exercise and the ensuing dynamic changes is a challenge that has been difficult to address up to now. It is well known that increase in HR during exercise is achieved through a combined effect of sympathetic activation and vagal withdrawal [4], yet the time course of these events is not fully elucidated. Less information is available regarding the changes in autonomic tone during recovery from maximal exercise. Arai et al [5] have suggested that the rapid decrease in HR after the cessation of exercise is due mainly to vagal reactivation, yet the time course for reactivation was not clearly defined.

Real-time, non-invasive analysis of spontaneous fluctuations in HR is used to evaluate autonomic control. During dynamic conditions such as maximal exercise, assumptions of stationarity are invalid; hence typical steady state analysis tools will provide inaccurate results. Time-frequency analysis must be used. To date, no studies have utilized the Wavelet decomposition to examine the instantaneous changes in heart rate variability (HRV) immediately following GXT. Continuous Wavelet Transform (CWT) offers superior time resolution and localization compared to other time-frequency methods.

We concentrate on the instantaneous fluctuations in HR in two main regions of power: a high frequency (HF) peak, located around the respiratory frequency and typically between 0.18 to 0.7 (during exercise) and a low frequency peak (LF) centered around 0.1 Hz. The HF peak reflects primarily vagal activity [6] while the LF content of HR fluctuations is used as an estimate of combined vagal and β sympathetic activity to the heart. Previous attempts to analyze HRV during exercise [7;8] were limited by restrictions of the classical spectral analysis tools in dealing with dynamic changes.

2. Methods

2.1. Patient population

We examined a database of 968 coronary artery disease (CAD) patients who underwent maximal exercise stress testing at the Procardia-Cardiostyle Maccabi Health Insurance Center. Patients were referred for testing by their primary care physicians or cardiologists. Referring physicians decided whether or not to continue cardio active medications on the day of the test. In this database, 108 out of the 986 patients demonstrated pathologic delta HR. We recruited 20 individuals from this database, with pathologic delta HR from their first GXT (within 6 mo. of second testing date) for a repeat GXT. The Helsinki committee of Maccabi Health Insurance approved this study and all patients signed an

informed consent form before participation. One patient in each group was taking beta-blockers on the day of the GXT. Data from two patients were discarded, one because of a very low respiratory frequency which did not allow discrimination between the LF and HF bands, and a second patient who did not complete stage 1 of the GXT for pulmonary reasons. Characteristics of the groups are as follows:

- **Pathologic delta HR**: n=5, age 54±13 years, height 168±7.6 cm, weight 75.5±16.6 kg.
- **Normal delta HR**: n=13, age 55±12, height 172.5±7.5 cm, weight 80.1±16.4 kg.

2.2. Signal acquisition and pre-processing

The following signals were sampled simultaneously, on-line at a sampling rate of 500 Hz using a Biopac multi-channel device with the Acknowledge software (MP100-BIOPAC system) and saved to a PC for off-line analysis.

- 12 lead ECG (4 leads recorded to Biopac)
- Respiration (Respitrace pneumoplethysmograph)

Respiration signals were low pass filtered (cut off frequency 4 Hz) and decimated to 10 Hz. R waves from the recorded ECG were detected automatically and detection was verified manually. Resulting RR intervals were interpolated to an equally spaced HR time series [9] and sampled at an effective sampling rate of 10 Hz. For spectral analysis, HR was filtered through a median high-pass filter to avoid the masking effect of non-stationarities on the spectrum.

2.3. Exercise testing

Seated resting ECG was recorded for 10 minutes followed by a maximal exercise stress test (90% age-predicted max HR), conducted on a treadmill using the Bruce protocol. Patients walked for 40 seconds after peak exercise, and then were seated on a chair placed on the treadmill for a 10-minute recovery period. Blood pressure was measured at rest, at the end of each workload, and every two minutes during recovery.

2.4. Time-frequency analysis

Time-frequency decomposition of the signals was performed by Continuous Wavelet Transform (CWT) as we have previously described [10]. This wavelet transform contains many aspects of the Selective Discrete Fourier Transform Algorithm (SDA) developed in our laboratory [11]. The CWT reflects the power of each spectral component at each point in time by applying a time window, the duration of which is inversely proportional to the analyzed frequency. Varying the window duration allows an improved time resolution for higher frequencies and improved frequency resolution for lower ones. CTW was calculated for HR over the entire recording period. LF and HF bands were defined individually (LF within 0.02-0.21; HF from upper LF boundary, up to 0.7) based on bandwidth and respiration rate. Time-dependent Power Integrals in the specific frequency bands were calculated and compared between groups.

2.5. Statistics

Power was calculated for every point in time during the recording. For statistical analysis, integrals were averaged every 15-seconds throughout rest and recovery. Because the duration of the GXT was different for each subject, peak exercise was labeled as 100% of exercise. The GXT was then divided into quarters so data could be compared at 25, 50, 75 and 100% of peak HR. Comparisons between groups were made by repeated-measures ANOVA and Independent Sample t-test. $p \leq 0.05$ was considered significant. Due to skewed distribution, all integrals were log transformed prior to statistical analysis. Data are shown as means±SE.

3. Results

Patients with pathologic delta HR had higher resting HR (97±19 bpm vs. 73±9 bpm), attained similar peak exercise HR (145±15 bpm vs. 142±17 bpm) and had lower delta HR in recovery than normals (12.5±4.4 bpm vs. 28.8±8.5 bpm) ($p<0.001$) (Fig 2, top panel).

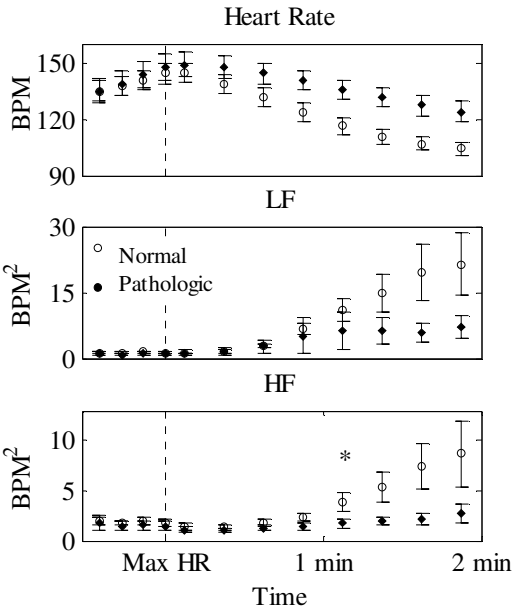

Figure 1: Average of HR, LF and HF power as a function of time. The vertical line corresponds to the time of max HR. Note significant difference in HF fluctuations at one-minute post exercise.

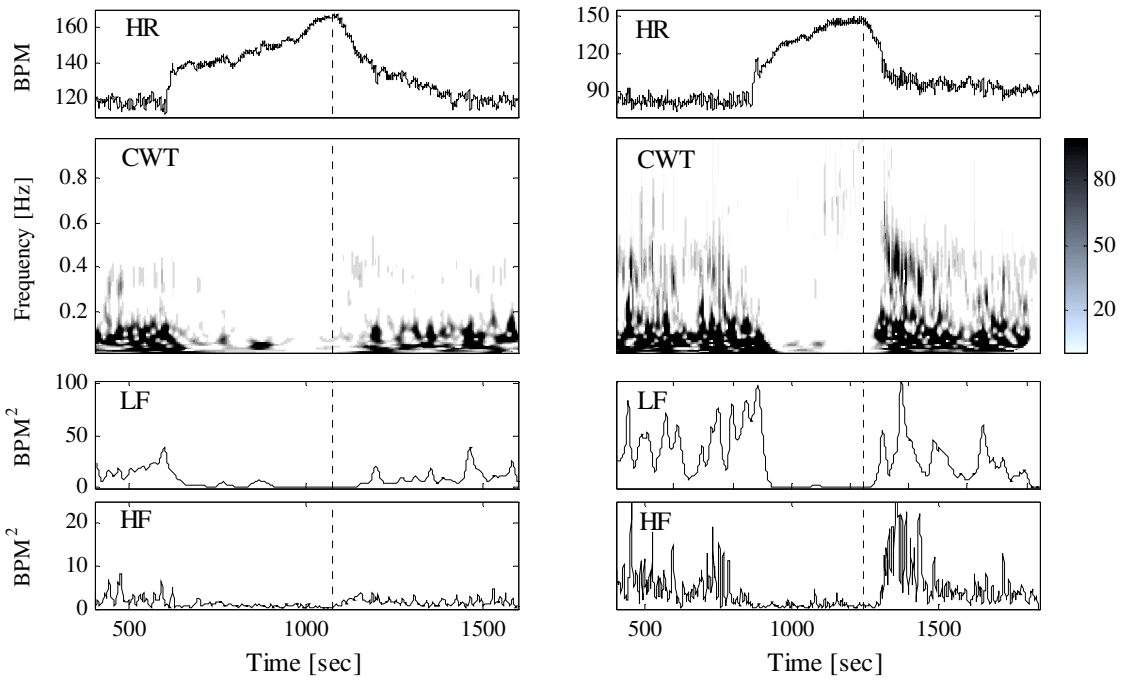

Figure 2: An Example of a patient with pathologic delta HR (left) and an individual with normal delta HR (right). Top panel - HR during entire GXT; Second panel - CWT of HR; Third panel - LF power of HR; Bottom panel - HF power of HR. Red line indicated peak exercise. Note reduced levels of LF and HF power in pathologic patient, as well as minimal reappearance of HF fluctuations at one-minute post exercise.

At minute one of recovery, patients who demonstrated pathologic delta HR had significantly lower power of HF fluctuations in HR ($p<0.05$, by t-test, Fig 1). There was a clear trend for HF to be lower in the patients with pathologic delta HR during the first 3 min of recovery, but perhaps because of the small sample size, it did not reach significance.

LF fluctuations in HR showed a marked trend of being reduced for the first four minutes of recovery in the individuals with pathologic delta HR, but this trend did not reach significance (Fig 1). LF/HF was not different between the groups from max to end of recovery, although here again, there was a trend toward lower LF/HF in individuals with pathologic delta HR.

4. Discussion

The aim of this study was to use special time-frequency analysis tools to examine HRV during dynamic conditions generated by maximal exercise and recovery. We examined CAD patients who had previously demonstrated pathologic delta HR upon recovery from maximal exercise, in an attempt to quantify vagal activity upon recovery from GXT. Patients who demonstrated pathologic delta HR had significantly lower HF fluctuations (vagal reactivation) at one min post peak exercise than individuals with normal delta HR. This indicates that a pathologic delta HR is indeed associated with abnormal vagal function upon recovery from maximal exercise, and that CWT is a powerful tool to examine the time-course of vagal reactivation.

LF and HF power decrease to near zero during maximal exercise in both normal and pathologic delta HR subjects. During intense exercise, the decrease in LF power likely indicates sympathetic saturation, and the decrease in HF, near complete vagal withdrawal. Shin [12] and others [5;7;13] have shown that LF and HF powers attenuate progressively with exercise and gradually recover post exercise. However, none of these studies have specifically examined the first minute of recovery from maximal exercise.

For the first time, we have shown that time-frequency analysis by CWT (SDA) is capable of detecting the time course of dynamic changes in autonomic activity during highly non-stationary conditions such as those found during maximal exercise and recovery. Using the CWT, we were able to distinguish significant differences in vagal reactivation at one-minute post peak exercise.

In this study, maximal exercise was defined as achieving 90% of age-predicted max HR, less strenuous

than symptom-limited max HR that Cole et al [1]and Watanabe et al [3]used. Imai et al [14] observed that HR decay for the first 30 seconds after exercise is prolonged by vagal blockade, but is nearly independent of exercise intensity. Hence we believe that using 90% of age predicted maximal HR is adequate for examination of vagal reactivation post exercise. Because high sympathetic activity and accumulation of anaerobic metabolites during intense exercise could attenuate post exercise vagal reactivation Imai suggest that sub maximal exercise should be used for assessment of the intrinsic potential of vagal reactivation from the initial post exercise HR decay.

In conclusion, this is the first time that significantly reduced HF fluctuations in HR upon recovery from GXT have been documented in patients with pathologic delta HR post GXT. It has been the assumption that reduced vagal activity is responsible for a pathologic delta HR during the first minute after maximal exercise. We have shown this assumption to be true in a small sample of patients with pathologic delta HR.

Acknowledgements

The Kodesh foundation and the Israeli Science Foundation partially funded this study.

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Address for correspondence
Professor Solange Akselrod
Department of Medical Physics
Tel Aviv University
Tel Aviv, Israel 69978
solange@post.tau.ac.il