Real-time Monitoring of Spontaneous Resonance in Heart Rate Variability

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Abstract— **The resonant characteristic of heart rate variability is usually generated using biofeedback and the external pacing of breathing, which is typically around 6 breaths/min (0.1 Hz), although the exact frequency varies between individuals. It was hypothesized that the actual resonant characteristic of heart rate actually depends on the current psychophysiological state of the subject; therefore, the real-team evaluation of this form of resonance is important for a variety of biofeedback applications. This paper presents an analysis of the spontaneous resonance of heart rate variability generated during singing and non-paced slow breathing after breathing exercises. Two methods for automatic analysis and characterization of heart rate variability resonance in real-time have been presented. The first method uses FFT-based spectral analysis, while the second method calculates the period and amplitude of the RR interval variation during each resonant cycle. The proposed methods were tested on a 45-min record from a chanting session and compared with manually annotated and measured periods.**

Keywords— **Heart Rate Variability, Respiratory Sinus Arrhythmia, Resonance, Spectral Analysis, Singing.**

I. INTRODUCTION

The main component of heart rate variability is respiratory sinus arrhythmia (RSA), generated by a combination of respiration-induced biochemical changes, changes in intrathoracic pressure, and central vagal stimulation [1][2]. Frequency of RSA component falls in High Frequency range of HRV (0.15-0.4 Hz) for more than 9 breaths/min. Slower breathing generates peak power of HRV in Low Frequency (LF) range (0.04-0.15 Hz). Vaschillo et al. found that the highest oscillation amplitudes are measured in the range of 0.055-0.11 Hz and explained sinus like oscillations of RR intervals by resonance among various oscillatory processes in the cardiovascular system [3][4]. Song and Lehrer found that the respiration rate of 4 breaths/min produced the highest amplitudes of HRV, while even lower rates (3 breaths/min) generated smaller amplitude [2]. Specific breathing techniques can also increase heart rate variability [5]. As reported earlier, trained individuals can breathe at very slow rates, such as yogic breathing techniques with 1 breath/min [6]. Very slow breathing with frequency of less than 0.04 Hz (more than 25 seconds/breath) generates a dominant respiration component in Very Low Frequency (VLF) band (0.003-0.04Hz) [7].

Voluntary control of cardiac variability through biofeedback may have important effects on autonomic health and has been used in treatment of asthma patients [4]. Traditional spectral analysis techniques use long time windows (2-10 minutes [7]), to facilitate characterization of changes at very low frequencies. However, long windows introduce processing latency. For example, processing with 10 min window would mostly reflect parameters in the middle of the window, and characterize cardiorespiratory variability with 5 minute latency.

This paper presents analysis of spontaneous resonance in real time with minimum latency. Algorithms are tested on a recording with spontaneous HRV resonance generated during long singing (chanting) session.

II. METHODS

Heart rate was measured using Actis wireless monitoring system with 1 ms resolution [8]. Beat to beat intervals (RR intervals) were interpolated with Fi=3.2 Hz interpolation frequency. Spectral analysis was performed with NFFT=64 samples (equivalent to 20 s window) and 128 samples (40 s window), and Hanning window. Frequency resolution was 0.05 Hz and 0.025 Hz respectively. Although traditional spectral analysis of HRV requires at least 2-5 min window, other processing methods with the minimum processing latency are necessary for biofeedback applications. Individual segments were detrended to eliminate mean value and the best straight-line fit linear trend. Short window size and detrending eliminated VLF components from the processed signal, which allows simplified calculation of the resonant spectral power with smaller number of samples. An LF/HF parameter is therefore calculated as a ratio of all spectral components below and above 0.15 Hz.

RR intervals were recorded throughout a singing session (Durga chanting). The subject was a healthy 26 year old female with 6 years of yogic experience. During recording, the subject was in Siddhasana position (sitting pose with straight spine and crossed legs) during the whole session (45 minutes).

Quality of resonance (Q) is evaluated as a ratio of power in LF and HF frequency band. Higher value of Q represents more intensive resonance. The FFT analysis of NFFT samples estimates spectral characteristic with resolution df:

$$df = {F_i}/{NFFT} \qquad (1)$$

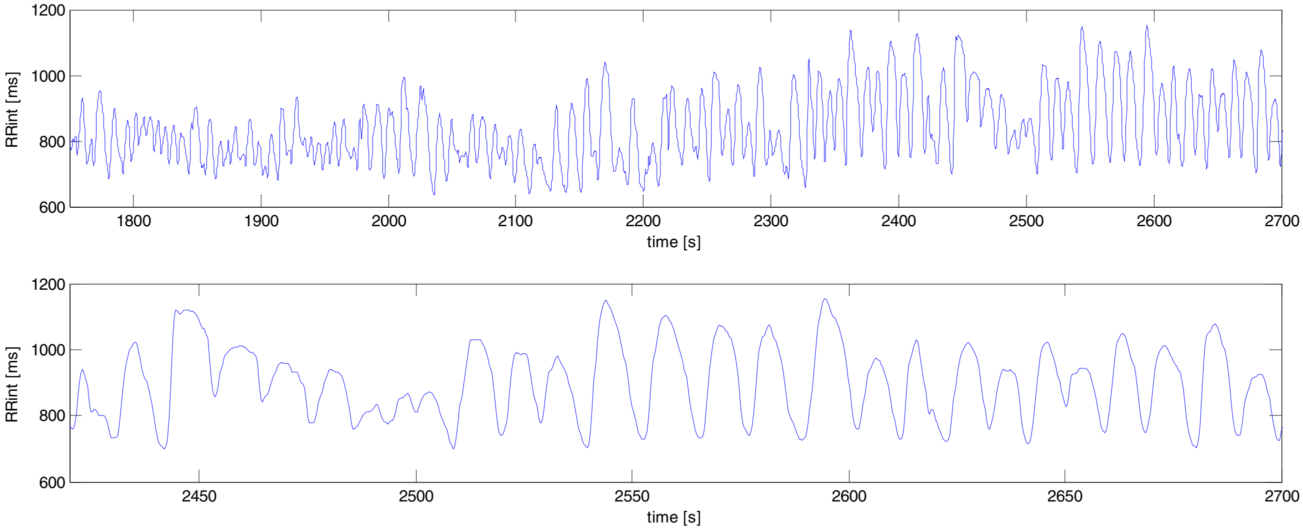

Fig. 1. Interbeat intervals (RR intervals) during Durga chanting as a function of time; Lower plot represents zoomed interval at the end of the chanting with prominent variations of RR intervals.

Sampling frequency is in this case equal to our interpolation frequency F_i. Maximum index of spectral component belonging to the LF frequency band is LFmax:

$$LF_{\max} = \left\lceil \frac{0.15Hz}{df} \right\rceil = \left\lceil \frac{0.15Hz}{F_i} \cdot NFFT \right\rceil \tag{2}$$

It is the An LF/HF ratio (Q) was calculated as:

$$Q = \sum_{i=1}^{LF\max} S_i \Bigg/ \sum_{i=LF\max+1}^{NFFT/2} S_i \tag{3}$$

A mean LF frequency F_m was calculated as:

$$F_m = \sum_{i=1}^{LF\max} S_i\ F_i \Bigg/ \sum_{i=1}^{LF\max} S_i \tag{4}$$

III. RESULTS

There was a clear trend of increased HRV power throughout the session, particularly at the end of session, as represented in Fig. 1. Spontaneous resonance can be clearly seen as a sine-wave like variation of RR intervals in several bursts during the session, and very stable and sustained at the end of the recording session.

Resonant characteristic of the LF/HF ratio - Q from (2), can be seen in Fig. 2. As expected, shorter FFT window creates much more variation, as seen in Fig. 2. However, we should have in mind that the short window (T_{win}=20s) represents slightly more than two cycles of the basic rhythm (0.1Hz). Longer processing window window (T_{win}=40s) represents at least four cycles of the basic resonant rhythm. Therefore, it is much more stable and could be used for biofeedback applications.

Smaller disturbances create large variation of the estimated parameter. Therefore, we experimented with the weighted parameters. We calculate weights as relative ratio of power at the given frequency:

$$W_i = S_i \Bigg/ \sum_{j=1}^{NFFT/2} S_j \tag{3}$$

Ideal resonance would have W_i equal to 1 for the spectral component that corresponds to the resonant frequency, and zero for all the other spectral components.

Every spectral analysis averages all the changes within the processing window, creating an emphasis to changes in the middle of the processing window. Therefore, applicability of the proposed approach was tested by comparing the results with manually annotated and measured results for each period of RR interval "sine-wave like" variation. A period is measured between two minimums of RR intervals, while amplitude is measured as the difference between the first minimum and maximum RR interval in the given period.

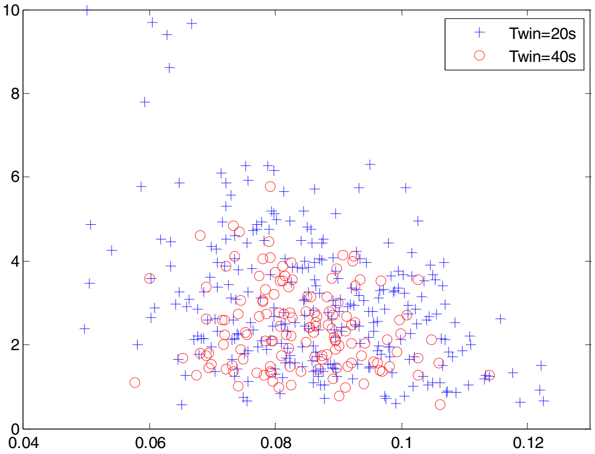

Fig. 2. Q factor (LF/HF ratio) as a function of the mean frequency F_m. for different processing windows T_{win}.

Weighted parameter can be calculated using individual weights (3). For example, weighted Q is calculated as:

$$Q_i^w = W_i\, Q_i \tag{4}$$

and represented in Fig. 3.

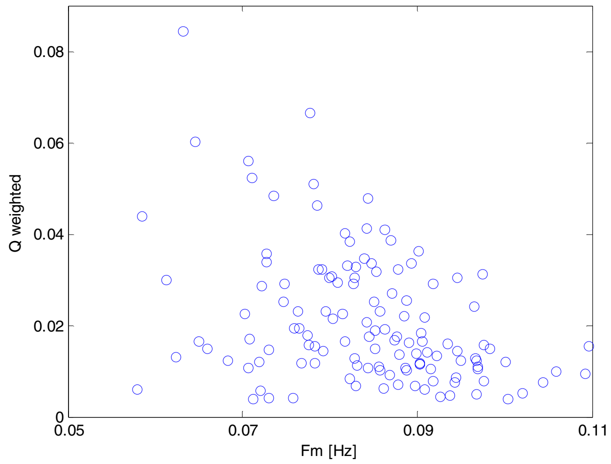

Fig. 3. Weighted Q factor (LF/HF ratio) as a function of the mean frequency F_m; T_{win} =40 s.

A peak to peak amplitude of the variation from signal in Fig 1b is represented as a function of the period in Fig. 4. Dynamics of amplitude and period of changes in time is presented in Fig. 5. We present both amplitude and period as relative changes (divided by the mean of the series) to represent a possible phase shift between the amplitude and phase. It is interesting to note that changes in amplitude very often precede period changes.

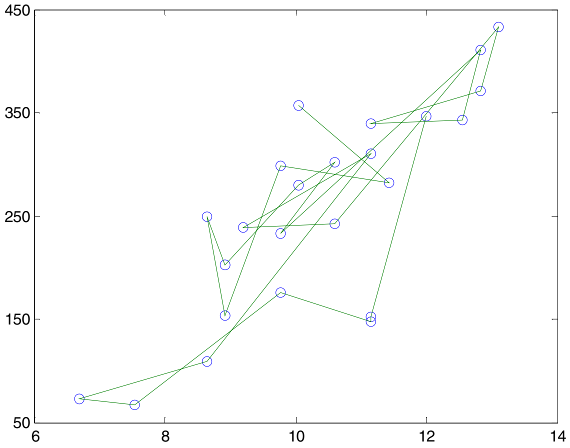

Fig. 4. Variation of peak to peak amplitude [ms] as a function of the period [s] in plot 1.b (time 2435-2690 s); manual annotation and measurement; mean period Tper=10.36 s; mean amplitude Aave=254 ms, maximum amplitude Amax=447 ms.

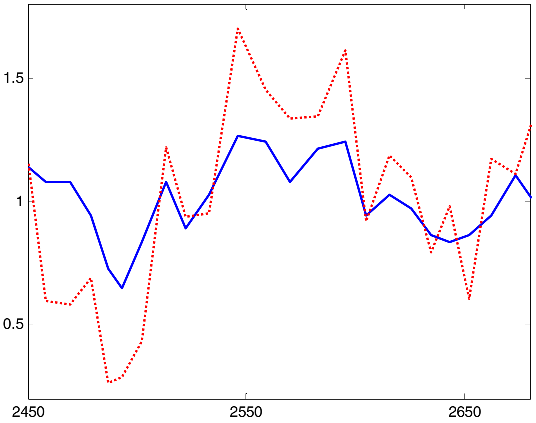

Fig. 5. Lower plot: relative change of the period Tper (solid line) and amplitude A (dotted line) in time (Fig. 1b).

Similar spontaneous decrease in maximum LF frequency from 0.0919 Hz to 0.07125 Hz ($t(7) = -3.255$, $p < .01$) after very slow yogic breathing was found. This indicates decrease of average breathing rhythm from 5.5 breaths/min before exercise to 4.3 breaths/min after exercise [6]. However, the exact breathing frequency varied from session to session, even for the same subject.

IV. CONCULSIONS

Real time monitoring of heart rate variability with minimum latency is very important for biofeedback techniques to provide user with an up to date snapshot of the autonomous nervous system and demonstrate the changes with minimum latency. This is particularly important in the beginning of a training session, when a person still learns how to breathe at resonant frequency [4]. Exact resonant frequency is individual and dynamic, even for the same person, from session to session, and throughout the session. Systematic practice gradually increases available physiological margin and establishes new resonant frequencies.

In this paper we demonstrated applicability of several spectral parameters for real-time biofeedback applications. For the given set of records we were able to use a 40 second window (128 point FFT), which provides 20 second latency. Some parameters could be still used with a 20 second window (10 second latency), but with significantly larger variation that can be an obstacle for user acceptance in biofeedback applications.

We plan to further investigate spontaneous resonances and their dynamics in other recordings, and apply them for real-time biofeedback training.

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