Time-Frequency Analysis of 24-Hour Heart Rate Fluctuation for the Characterization of Very Low-Frequency Component

Hsiao-Lung Chan†, Jiunn-Lee Lin‡, Chao-Cheng Du‡, and Chien-Ping Wu †
†Department of Electrical Engineering, ‡Department of Internal Medicine
National Taiwan University, Taipei, Taiwan, Republic of China

Abstract - A smooth pseudo Wigner-Ville distribution was employed to investigate both time and frequency characteristics in very low-frequency component (less than 0.04 Hz) of 24-hour heart rate fluctuation. In some of heart failure, we could see remarkable and very low-frequency oscillations on the Wigner-Ville distribution, which are related to Cheyne-Stokes respiration. However, the Wigner-Ville distribution of normal subjects had not such oscillations, but more random spectral characteristics instead. Furthermore, we calculated $1/f^\alpha$ regression slopes of average spectrum to be a crude estimate of fractal dimensions. The slopes are more negative in heart failure than normal (-1.866 ± 0.888 vs. -0.957 ± 0.180 $p <$ 0.005), which associates a loss of dimensionality of heart rate fluctuation in heart failure.

INTRODUCTION

Spectral analysis of heart rate variability provides a way to understand the different control mechanisms of the autonomic nervous system. In previous researches[1], the high frequency fluctuations of heart rate (approximately 0.15-0.40 Hz) were regarded as vagal control, and were correlated with respiration. And, the low frequency fluctuations (approximately 0.04-0.15 Hz) were due to both sympathetic and vagal control. However, for the implicated mechanism of very low-frequency fluctuations (less than 0.04 Hz), there were some hypothesis and observations, such as renin-angiotension regulation [1], temperature regulation [2], a chaotic behavior[3], and a long-wavelength oscillation in heart failure[4]. In clinical study, power in very low-frequency band differentiated the heart failure group from the normal group[5]. Moreover, it had strong association with mortality after myocardial infarction[6]. Thus, we regarded it might imply some physiological or pathological information in very low-frequency heart rate.

One problem exists in the analysis of very-low frequency heart rate : what is the proper size of time window for spectral analysis? A particular window should be appropriate for a particular signal to give better frequency resolution. Longer window could provide better frequency resolution, but would smear the time-varying characteristic of signals (*ie*, poor time resolution). To overcome this problem, we employed Wigner-Ville distribution to reveal possible phenomenons in very low-frequency band of 24-hour heart rate.

METHODS

A. Subjects and preliminary processing

Thirteen heart failure patients and fourteen normal subjects were included for this study. All subjects underwent 24-hour Electrocardiogram recording. ECG signals were digitized into PC for QRS detection and verification. The instantaneous heart rate were equal-sampling (2 Hz) using cubic spline interpolation. In order to reduce the heavy computation in Wigner-Ville distribution, the sampling rate of heart rate was further reduced to 0.2 Hz. Before subsampling, original heart rate were filtered with a FIR low-pass filter with 0.08 Hz cut-off frequency to avoid aliasing.

B. Smooth pseudo Wigner-Ville distribution (SPWVD)

The SPWVD of a heart rate signal $s(n)$ is expressed as follows :

$$SPWVD(n,k) = \sum_{i=-N+1}^{N-1} |h(i)|^2 \left[\sum_{m=-M+1}^{M-1} g(m) \, z(n+m+i)z^*(n+m-i) \right] exp(-j\frac{2\pi}{N}ik) \quad (1)$$

where $h(i)$ is a Gausian window, $g(m)$ is a rectangular window, and $z(n)$ is the analytic signal associated with real heart rate signal $s(n)$. It is calculated in the time dormain as follows :

$$z(n) = s(n) + jH[s(n)] \quad (2)$$

where $H[.]$ is Hilbert transform.

Using windows of $h(i)$ and $g(m)$, it allows independent smoothing in both directions, frequency and time , by selecting different window size, $2N-1$ and $2M-1$ respectively [7,8]. Also, it can reduce cross terms which may encounter in WVD. The use of the analytic signal could avoid low-frequency artifacts and aliasing components produced in the real Wigner distribution [9].

C. $1/f^\alpha$ regression slope

In order to study the fractal dimensions of heart rate fluctuation, the average spectrum, time integration of Wigner-Ville distribution, were characterized as an inverse power-law ($1/f^\alpha$-like) spectrum within the following frequency band : the highest frequency was set to 0.04 Hz, and the lowest frequency was the peak frequency associated maximum power below 0.04 Hz. With steeper slope α, the fractal dimension of heart rate fluctuation would be smaller, and vice versa.

RESULTS

Figure 1 shows the Wigner-Ville distribution of 24-hour heart rate fluctuation in a heart failure patient. One can easily see remarkable and very low-frequency oscillations during night, and more random spectrum in the other time. These oscillations are regarded as Cheyne-Stokes respiration (CSR)[3]. It implies that high degree freedom of heart rate fluctuation have become locked into a single wavelength during CSR. Meanwhile, the oscillation frequency, amplitude, duration , and occurrence time could be identified. However, the Wigner-Ville distribution of normal subjects have not such oscillations, but more random spectral characteristics instead.

Comparing regression slopes of average spectrum, we found it has statistical differences ($-1.866 \pm 0.888 vs. -0.957 \pm 0.180 p < 0.005$). This result demonstrats that heart failure subjects yield more negative slopes than normal subjects, that is, it is associated with a loss of dimensionality of heart rate fluctuation in heart failure.

DISCUSSION

Very Low-frequency power of heart rate accounts most portion of total power in the spectrum of 24-hour heart rate. Unlike other higher frequency power, it is less directly related to the action of vagal or sympathetic system. By the tranform of 24 heart rate to Wigner-Ville distribution, it not only provides more high-resolution spectral characteristics, but also reveals both frequency-varying and time-varying characteristics of signal. Therefore, it will be helpful for observing the very low-frequency dynamics of the regualtion of the cardiovascular system.

Although there would exist cross terms in the Wigner-Ville distribution, these could be improved by appropriate selection of smoothing window ($g(m) \& h(i)$) [8]. In addition, the computation work of this SPWVD is less heavy, compared with other interference-reduced WVD [9]. So it is suitable for signal with a large amount of data , such as 24 heart rate fluctuation signal.

ACKNOWLEDGEMENT

We are grateful for the support of grants NSC 82-0404-E002-397 from the National Science Council, Taiwan, Republic of China.

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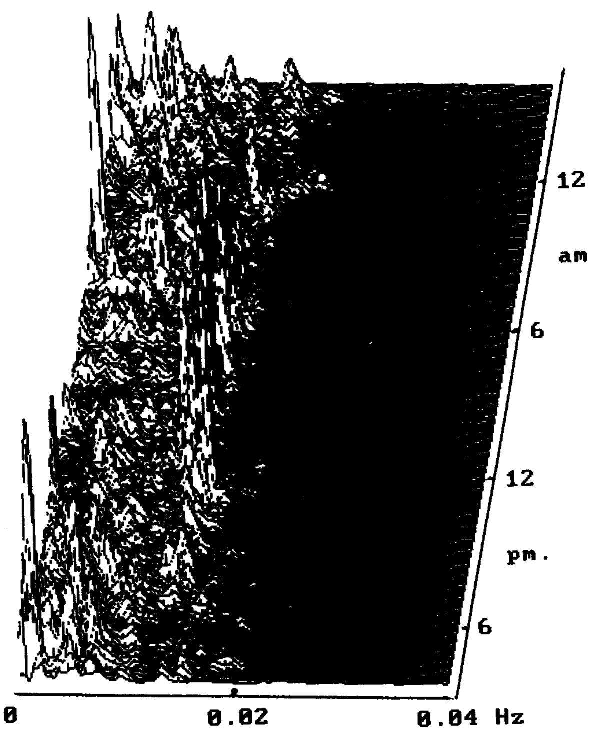

Figure 1: SPWVD of one heart failure patient. There are about 0.015 Hz low frequency oscillations during night, and are regarded as Cheyne-Stokes respiration.