Multifractal Analysis of the Day and Night Characteristics of Heart Rate Variability

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Abstract

The RR heart rate variability characteristics of normal subjects were studied to compare the multifractal characteristics during day and night. The RR intervals were obtained from 24-hour digital Holter ECG recordings of normal subjects, starting at midday. Each 24 hour period was split into 4 blocks of 6-hour which were analysed separately. The overnight period was fully contained in the third block, between midnight to 6 a.m.

The 6-hour blocks were analysed using a wavelet transform multifractal formalism. Each spectrum peaked between the Hurst exponent (h) limits of 0.07 and 0.29. In one subject the overnight spectrum did not have a consistent overnight peak and could not be analysed. In the subjects with well-defined spectral peaks, the overnight peak position of h tended to be greater than that for any of the other three 6-hour periods, indicating that the fractal characteristics of the RR intervals differ during the overnight sleep period.

1. Introduction

The awake and asleep states are different but highly complex physiologic states which can be studied using 24-hour Holter ECG monitoring. The power spectra of the associated *RR* intervals indicate the presence of long range correlations [1]. Such second order fractal characteristics have been well studied using the detrended fluctuation analysis technique [1]. These long range correlations are consistent with anti-correlations which drive the system away from extreme behaviour. However, the complexities of these states can be unraveled further using higher order fractal statistics, in particular by multifractal [2] scaling analysis.

In this study, the *RR* variability in 24-hour ECG Holter recordings of normal subjects was analysed from a multifractal perspective using a wavelet-based partition function [3] method. The aims were to study how the variability is characterized using a spectrum of scaling indices and to quantify the difference in the variability between awake and asleep states.

2. Methods

2.1. Subjects

About 10^5 *RR* intervals were used from each of the normal subjects. The data were obtained from 24-hour digital Holter ECG recordings of the subjects, starting at midday. All *RRs* were then measured and displayed on a computer screen along with the ECG to enable artifactual intervals to be corrected. Each 24 hour period was split into 4 blocks of 6-hours. The asleep state corresponded to the third block, between midnight to 6 a.m. The *RR* intervals from a typical normal subject during the awake state and the asleep state are shown in Fig. 1.

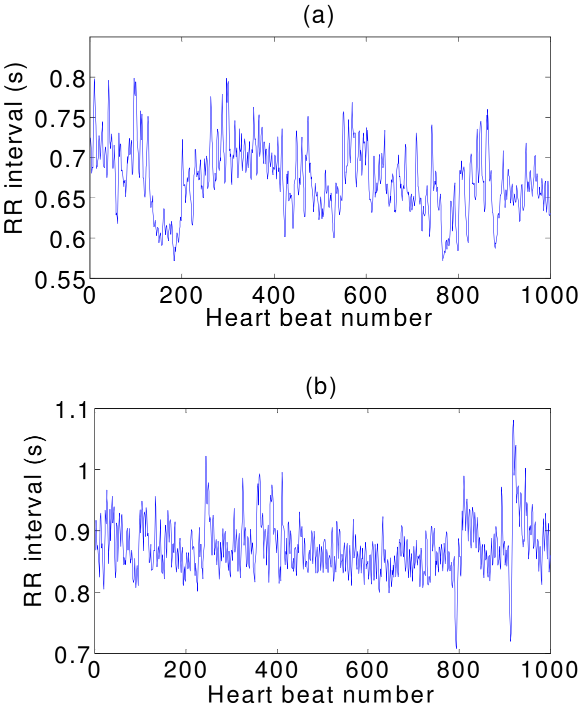


Figure 1. Typical *RR* time-series of a normal subject during (a) the awake state and (b) the asleep state. A segment of 1000 *RR* intervals is shown in each case.

2.2. Analysis

The wavelet transform is obtained by projecting the signal onto a set of basis functions, obtained by dilating and translating a single prototype wavelet $\psi(t)$. Thus, the continuous wavelet transform $T_{\psi}(b, a)$ of a signal $f(t)$ is defined as

$$T_{\psi}(b, a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t)\psi\left(\frac{t-b}{a}\right) dt$$

where $\psi(t)$ is the analyzing wavelet, $a\ (>0)$ is the scale parameter and b is the position parameter. The polynomial orthogonality property of wavelets [3] is used to extract the singular features of a fractal signal. A partition function $Z(q, a)$ is defined in terms of the powers of order q of the wavelet transform amplitudes at positions where the transform has local maximum moduli for an analyzing scale a. These local maxima lie on maxima lines l [4]. The set of maxima lines define a wavelet transform skeleton. In the limit $a \to 0^{+}$, it is expected that

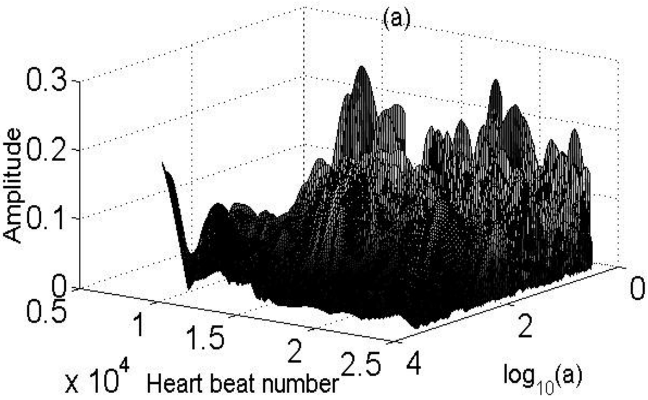
$$Z(q, a) \sim a^{\tau(q)}.$$

A wavelet transform multifractal formalism relates the singularity spectrum $D(h)$ to the characteristic exponent $\tau(q)$ through a Legendre transformation, h being the Hurst exponent [3].

3. Results

3.1. Wavelet transform

The wavelet transforms of two 6-hour blocks, one for an awake state and the other for an asleep state are shown in Fig. 2. The analysing wavelet was the third derivative of the Gaussian function.



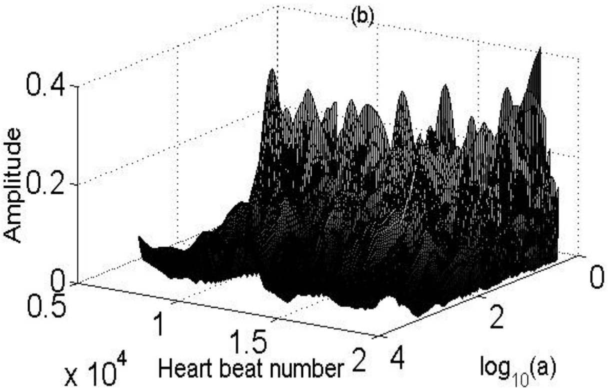


Figure 2. Wavelet transform of the *RR* interval time-series: (a) the awake state and (b) the asleep state.

3.2. Wavelet transform skeleton

The wavelet transform skeletons corresponding to Fig. 2(a) and Fig. 2(b) are shown in Fig. 3 below.

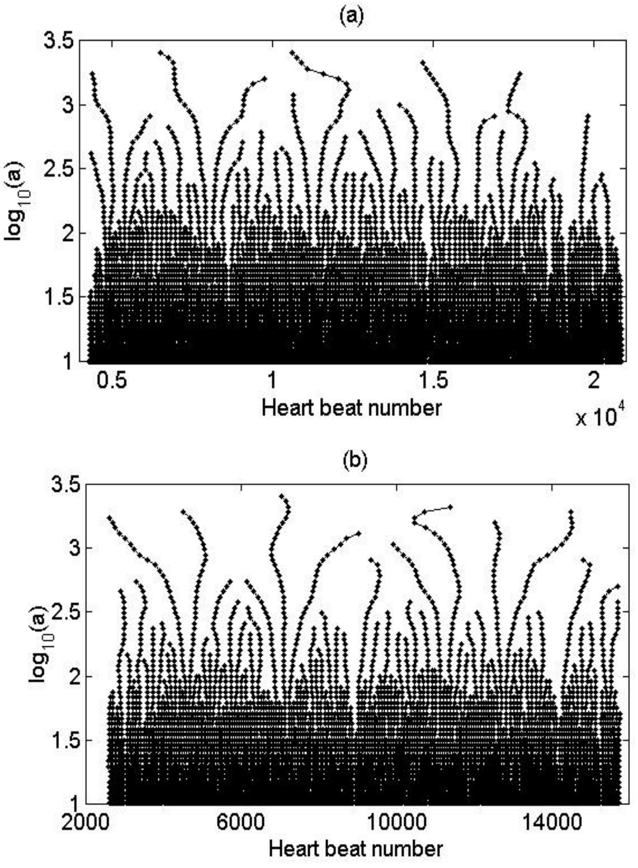


Figure 3. Wavelet transform skeleton associated with Fig. 2: (a) the awake state and (b) the asleep state.

3.3. Partition function and partition function scaling

Fig. 4 shows the variation of the partition function $Z(q, a)$ for q ranging from -5 to $+5$. The scaling of the partition function with the analyzing scale a generates a characteristic exponent $\tau(q)$ from which the spectrum of singularities is computed using a Legendre transformation.

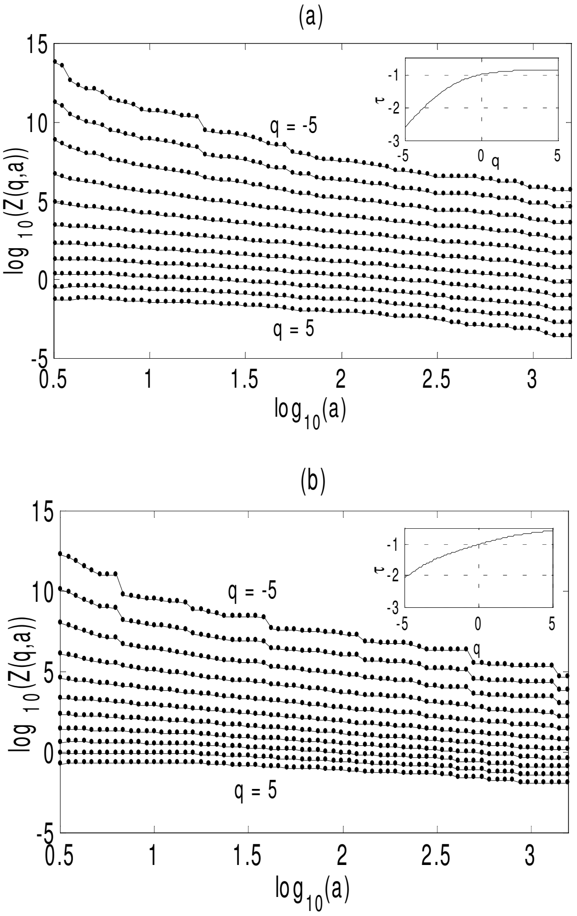


Figure 4. Scaling of the partition function $Z(q, a)$ with the analyzing scale a: (a) the awake state and (b) the asleep state. The inset shows the characteristic exponent spectra.

3.4. Multifractal singularity spectrum

The multifractal singularity spectrum for a subject in the awake state is shown in Fig. 5(a). Fig. 5(b) shows the spectrum for the asleep state. These results are typical in that the singularity spectra are smooth and defined over a finite range of Hurst exponents. Also, the peak position of the Hurst exponent in the asleep state is greater than in the awake state, indicating less anti-correlated behaviour in the asleep state.

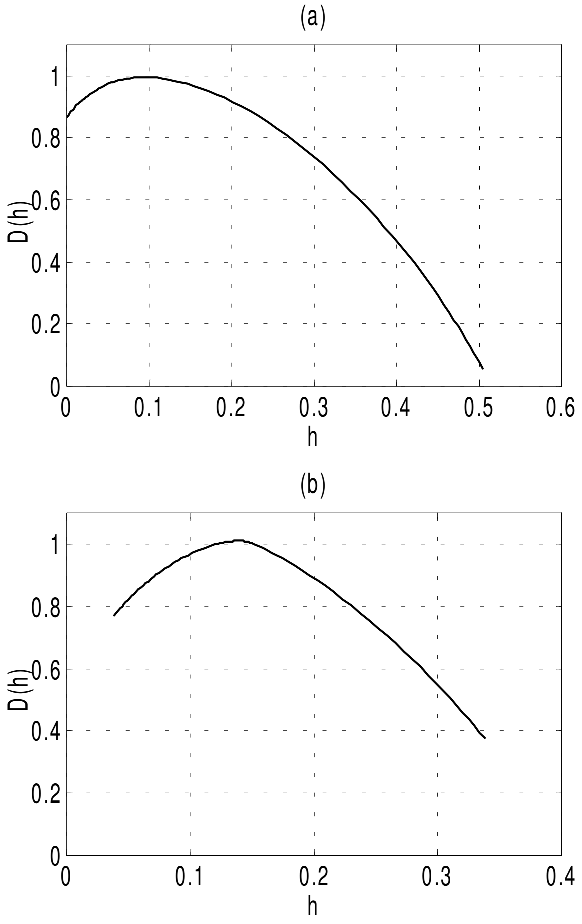


Figure 5. The spectrum of singularities for (a) the awake state and (b) the asleep state.

4. Discussion

The main objective of this study was to analyse the *RR* variability in 24-hour Holter ECG recordings from a multifractal perspective and to quantify any difference between the awake and asleep states of normal subjects. Generally, the singularity spectra are smooth and are defined over a finite range of Hurst exponents. This confirms the multifractal distribution of the singularities. Also, the peak position of the Hurst exponent in the asleep state tended to be greater than in any of the 6-hour awake states. This indicates that the asleep state is less anti-correlated than any of the awake states. However, the asleep and awake states are found to be of nearly equal complexity. This is in line with the recent findings that the multifractal complexity of heart rate variability does not arise from the subject's behaviour [5] but is an intrinsic physiologic feature. For example, the asleep state is a complex recuperative state involving REM and non-REM stages. The nature of these stages and the transitions between them need further analysis. In addition, Ivanov et al. [6] have obtained a greater anti-correlated behaviour for the asleep state using the technique of detrended fluctuation analysis. This different result is currently being investigated.

Acknowledgements

SKR is grateful for the kind hospitality of the Regional Medical Physics Department at Freeman Hospital and acknowledges discussions with Dr S S D Goorah.

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