

The HRV Multifractality Spectrum and not the Power Spectrum is Altered in Paraplegic Individuals with Low-Level Lesion

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Abstract

The autonomic nervous system may contribute to the multifractal-multiscale dynamics of heart rate variability (HRV). Aim of this work is to evaluate multifractal-multiscale features of HRV complexity when the integrative autonomic regulation is altered. We recorded R-R intervals for 10 minutes in 14 spinal cord injured (SCI) individuals with lesion below the 12th thoracic vertebra (which have an intact autonomic cardiac innervation but a partially altered autonomic integrative control) and in 34 matched able-bodied (AB) controls. We calculated powers spectra by FFT and generalized Hurst coefficients, $\alpha(q, \tau)$, with scales τ between 6 and 120 seconds and with $-4 \leq q \leq 4$, by multifractal multiscale detrended fluctuation analysis. At each scale we calculated $SD(\tau)$, standard deviation of $\alpha(q, \tau)$. $SD(\tau)$ is ≥ 0 and tends to zero at scales where the series is monofractal. AB and SCI groups were compared by Mann-Whitney test. While SCI and AB spectra were similar, $SD(\tau)$ was significantly lower at $\tau < 7$ s and at τ around 24 s in the SCI group. Thus, in low-level SCI individuals, the multifractal-multiscale detrended fluctuation analysis of HRV reveals alterations in the autonomic integrative control undetected by traditional spectral analysis, likely due to loss of multifractality at specific scales.

1. Introduction

Fractal analysis is becoming more and more popular for assessing the complex dynamics of cardiovascular time series [1]. In the field of heart-rate variability (HRV), the fractal characteristics are usually assessed by estimating the self-similarity scale coefficient α (strictly related to the Hurst's exponent) with the detrended fluctuation analysis method (DFA) [2]. Briefly, given a time series of N samples x_i with $i=1 \dots N$ and mean μ , the summation series y_i

$$y_i = \sum_{j=1}^i (x_j - \mu) \quad (\text{eq.1})$$

is split into M blocks of n consecutive samples.

DFA is based on the calculation of the variability function $F(n)$:

$$F(n) = \frac{1}{M} \sum_{k=1}^M \sqrt{\sigma_n^2(k)} \quad (\text{eq.2})$$

with

$$\sigma_n^2(k) = \frac{1}{n} \sum_{i=I_k}^{I_k+n-1} (y_i - p(i))^2 \quad (\text{eq.3})$$

the variance of the n consecutive samples in the k -th block, after detrending with the least-square fitting polynomial $p(i)$. The scale coefficient α is the slope of the regression line fitting $F(n)$ over n in a log-log scale.

On one hand, some authors extended this single-scale approach estimating a continuous profile $\alpha(n)$, function of the scale n , by calculating the slope of the regression line over a running window centered on n [3]. In this way, DFA provides a multiscale representation of the fractal structure of HRV. On the other hand, DFA has been extended for estimating multifractality, defining the variability function as:

$$\begin{cases} F_q(n) = \left(\frac{1}{M} \sum_{k=1}^M (\sigma_n^2(k))^{q/2} \right)^{1/q} & \text{for } q \neq 0 \\ F_q(n) = e^{\frac{1}{2M} \sum_{k=1}^M \ln(\sigma_n^2(k))} & \text{for } q = 0 \end{cases} \quad (\text{eq.4})$$

If α , in this case estimated as slope of the regression line fitting $F_q(n)$ over n in a log-log scale for each q separately, depends on q , $\alpha(q)$, the series is multifractal [4].

More recently, the two approaches have been combined to provide a multifractal-multiscale representation of the scale coefficients, $\alpha(q, n)$, that allows quantifying the degree of multifractality separately at each scale [5]. In this way, DFA provides a more detailed and complete description of the complex dynamics of HRV.

Aim of this study is to apply the novel multifractal-multiscale approach for evaluating whether DFA can

assess alterations of the integrative autonomic control of circulation by identifying loss of multifractality at specific scales. For this aim, we analyzed heart rate recordings in spinal-cord injured (SCI) individuals with a low spinal lesion. These subjects have intact cardiac autonomic innervations but suffer from an impaired sympathetic control of the lower limbs and vascular districts, therefore representing a model of a partially impaired integrative autonomic control. We may expect that an impaired integrative control is associated with a loss of cardiovascular complexity.

2. Methods

We recorded R-R intervals (RRI) for 10 minutes in 14 spinal cord injured (SCI) individuals with lesion below the 12th thoracic vertebra and in 34 matched able-bodied (AB) controls. All participants were in sitting position at rest. RRI beat-by-beat series were interpolated evenly at 5 Hz. The Welch periodogram was estimated by FFT with 90% overlapped Hann windows of 180 s length, and smoothed with a broadband procedure [6]. Power spectra were integrated over the very-low frequency (VLF, 0.005–0.04 Hz), the low-frequency (LF, 0.04–0.15 Hz) and the high-frequency (HF, 0.15–0.40 Hz) bands. Further details on spectral analysis can be found in [7].

The multifractal-multiscale DFA was performed on the beat-by-beat RRI series. To minimize the estimation variability of $F_q(n)$, the equation 1 was calculated splitting the series into maximally overlapped blocks of size n , as described in [8]. The multifractal variability function, $F_q(n)$, was estimated for a set of scales, n_k , with k between 1 and K , equispaced over the logarithmic scale. Called N the length of the time series, K was set equal to $N/4$. We considered 9 values of the q parameter, equispaced between -4 and +4. Local scale exponents $\alpha_B(q, n_k)$ were calculated at scales n_k , with k between 2 and $K-1$, as the derivative of $\log F_q(n)$ vs. $\log n$:

$$\alpha_B(q, n_k) = \frac{\log F_q(n_{k+1}) - \log F_q(n_{k-1})}{\log n_{k+1} - \log n_{k-1}} \quad (\text{eq.5})$$

To move from the beat-domain into the time-domain, we applied the transformation:

$$\alpha(q, \tau_k) = \alpha_B(q, n_k) \quad \text{with } \tau_k = n_k \times 60 / HR_m \quad (\text{eq.6})$$

where HR_m is the mean heart rate, in bpm. The multifractal-multiscale surface of DFA coefficients, $\alpha(q, \tau)$, was obtained linearly interpolating $\alpha(q, \tau_k)$ over the time scale between 5s and 128 s.

Furthermore, we calculated a concise index of the degree of multifractality at each scale separately. For any given τ' scale, we calculated $\alpha_{SD}(\tau')$ defined as the standard deviation of the nine $\alpha(q, \tau')$ values estimated for each of the nine parameters q we considered. The $\alpha_{SD}(\tau)$ index is expected to be substantially greater than zero at scales

were the time series is multifractal, and to tend to zero at scales with a monofractal dynamics.

3. Results

The two groups were very well matched in terms of age (AB: 39.3 +12.1; SCI: 40.9 +10.0 yrs), BMI (AB: 24.7 +2.6; SCI: 25.5 +4.8 kg/m²) and gender ratio (AB: 5/29; SCI: 2/12 Females/Males).

The average power spectra calculated over the AB and SCI groups were practically superimposable. The power spectra in the VLF, LF and HF frequency bands are reported in table 1.

Table 1. Power spectra of RRI in AB and SCI groups, as mean (SD), with p the statistical significance of the difference between groups.

Spectral Parameter	AB	SCI	p
VLF	2.8+0.4	2.9+0.3	0.34
LF	2.8+0.5	2.8+0.4	0.84
HF	2.3+0.5	2.3+0.5	0.83
LF/HF	0.6+.03	0.6+.02	0.72

VLF, LF and HF powers as \log_{10} ms²/Hz; p after Mann-Whitney test

The LF and HF powers and their ratio were identical in the AB and SCI groups. The VLF power was slightly greater in the SCI group, the difference however being far from the statistical significance.

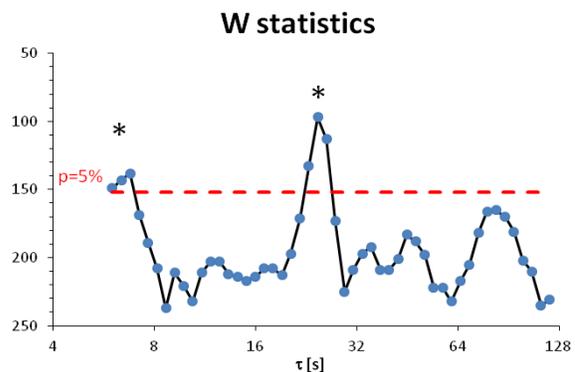


Figure 1. Mann Whitney W statistics derived by testing the difference between AB and SCI groups in $\alpha_{SD}(\tau)$; the horizontal dashed line is the statistical threshold at 5% significance. W values above the threshold are associated with significant differences and are marked by asterisks.

By contrast, differences between groups were found in $\alpha_{SD}(\tau)$, index representing multifractality at each scale separately. Figure 1 represents the W statistics resulting from the Mann Whitney test comparing AB and SCI

group. The statistics is represented as function of the scale τ . The figure points out significant differences at scales $\leq 7s$ and at scales around 24 s.

At both these scales $\alpha_{SD}(\tau)$ is significantly lower in the SCI group. In particular, at $\tau \leq 7s$ $\alpha_{SD}(\tau)$ is 3.77 ± 0.95 in the AB group, 2.30 ± 0.40 in the SCI group (values as median \pm standard error of the median); at $23s \leq \tau \leq 26s$, $\alpha_{SD}(\tau)$ is 1.80 ± 0.19 in the AB group, 0.99 ± 0.20 in the SCI group.

4. Discussion

The SCI group represents a human model of intact autonomic cardiac innervation with impaired autonomic integrative control of circulation due to an altered sympathetic control of the lower vascular districts. This human model is characterized by preserved spectral components, as testified by the comparison of their power spectra with those of a group of controls with the same age, body mass and sex ratio.

By contrast, clear alterations appear in the HRV dynamics when complexity features are assessed by means of the multifractal-multiscale approach to DFA. The comparison with the control group points out that the alterations consists in a loss of multifractality of HRV, concentrated at specific scales.

Therefore, the multifractal-multiscale DFA of cardiovascular time series appears to be a promising tool for detecting alterations in the autonomic integrative control of circulation. Such alterations may go completely undetected if evaluated by traditional spectral methods.

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