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Multifractal characterization of blood pressure dynamics: stress-induced phenomena

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Abstract

We investigate the scaling features of blood pressure dynamics in healthy rats by means of the wavelet transform modulus maxima method. We discuss how stress affects the phenomenon of multifractality in the cardiovascular dynamics. Typical reactions to stress are considered, and distinctions in the stress-induced effects for male and female rats are reported.

1. Introduction

Many biological time series are highly nonstationary and inhomogeneous. In particular, nonstationary dynamics represents a typical feature of a cardiovascular system [1]. This nonstationarity can be caused by several reasons. On the one hand, it arises from changes in environmental conditions since various external stimuli, stresses, even simple changes of a body position affect the heart rate and statistical characteristics of the heart activity. As a result, the cardiovascular system may demonstrate long transient processes in the beat-to-beat dynamics. On the other hand, the nonstationarity can vary from healthy to pathological regimes [2], the latter allows to assume that environmental conditions are not the only origin of the discussed phenomena.

Processing of biomedical data is often realized within the framework of the following ideology: It is supposed that short fragments of experimental time series are close enough to stationary signals, and such fragments can be studied by means of traditional techniques of the statistical analysis. The given approach seems to be useful if the nonstationarity is associated only with the low-frequency region of power spectrum with respect to the rhythms of interest from the physiological point of view. Such nonstationarity is treated as a trend and may be simply filtered out from the data [3]. However, the given situation is not always true for real time series. As an example, besides a slow "floating" of the mean value, instantaneous frequencies of various rhythmic components can display complex and irregular fluctuations,

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i.e., effects of nonstationarity may be associated with the higher frequencies as well. An analysis of such time series using traditional statistical or spectral approaches can lead to various misinterpretations of the obtained results.

From the viewpoint of possible applications the attractiveness of a particular technique for signal processing depends on its generality (i.e., its lack of restrictions with respect to the homogeneity and the stationarity of the data series). Among such rather universal (and at the same time effective) tools the detrended fluctuation analysis [4,5] and the wavelet based techniques [6–8] are particularly useful. The given tools have found many successful applications (see, e.g., [9–11]). A potentially promising topic in physiological data analysis was offered by recent studies of Ivanov et al. [12,13]. Using the wavelet based multifractal formalism [8] they have shown that physiological signals under healthy conditions are related to a class of multifractal objects. According to Refs. [12,13], multifractal properties of the heart rate dynamics may differ in health and disease, that is why scaling characteristics of the considered formalism become of interest for classification of a state of biological system.

In the given paper, we discuss how stress affects the features of multifractality in the cardiovascular dynamics. Using experimental recordings of arterial blood pressure (BP) in healthy rats we show that the stress-induced changes of multifractality may be different for male and female organisms. We conclude that stress typically decreases "smoothness" of blood pressure dynamics for male rats and sometimes reduces the degree of multifractality. A multiscale structure of BP signals for females is less sensitive to stresses.

2. Experiments

Experiments were performed on 18 white rats weighting from 250 to 300 g. (10 males and 8 females). Each of them was instrumented with intra-arterial polyethylene catheter for direct blood pressure measurements. Arterial blood pressure was recorded in freely moving rats during 30 min at rest conditions, then during 15 min at stress and during 60 min next day after stress (a recovery process). In our experiments, a model of immobilization stress was considered when a rat has no possibility of freely moving. BP signals were acquired on the PC based multichannel complex PowerLab/400 ML401 using the software Chart 4 (ADInstruments Ltd., Australia). Data was collected with the sampling rate of 500 Hz.

In the course of data preprocessing the "clear" fragments of BP signals were chosen for each stage of experiments (fragments of about 10 min without transient processes and artifacts). Taking the given fragments, a transition from original time series (Fig. 1a) to the so-called point processes was performed, the latter being sequences of time intervals between the local maxima of BP signal (Fig. 1b). Aiming to provide more precise determination of the maxima positions, BP signals were interpolated by splines. The extracted sequences of times represent an analogue of heartbeat intervals of an electrocardiogram. Such sequences were further analyzed to reveal stress-induced changes of their complex multifractal structure.

3. WTMM-method

Numerical analysis performed in our work was based on the wavelet transform modulus maxima (WTMM) method [7]. This is now one of the commonly used approaches to study multiscale structures in complex time series. Since the wavelets represent well localized functions, they are appropriate to the processing of inhomogeneous time series. The attractiveness of using the WTMM method is associated also with the possibility it provides of analyzing a wide range of scales and a broad spectrum of scaling characteristics (from small fluctuations and weak singularities to large fluc-

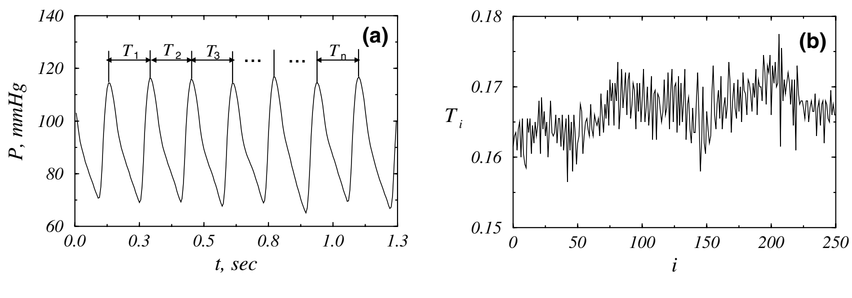

Fig. 1. Blood pressure signal (a) and the sequence of time intervals between the local maxima of the given signal (b).

tuations and strong singularities). This is an advantage of the wavelet-based technique in comparison with the previously suggested structure function method [14] that investigates multiscale properties by calculating the moments of the probability density function. The WTMM-approach, described in details in [8], performs the numerical quantification of a time series by means of the so-called *singularity spectrum* $D(h)$, where D is the fractal dimension of the subset of the data characterized by the Hölder exponent h.

The analysis of a function $f(x)$ with the discussed approach is performed in the following way. In the first stage, the wavelet transform coefficients are estimated:

$$T_\psi[f](x_0,a) = \frac{1}{a}\int_{-\infty}^{\infty} f(x)\psi\left(\frac{x-x_0}{a}\right)\mathrm{d}x, \quad (1)$$

where $f(x_0)$ is a distribution at a point x_0 (for sequences like interbeat intervals a random walk displacement may be considered as $f(x)$), a is the scale parameter, and ψ is the wavelet "mother" function that can have a rather arbitrary shape, although it should be soliton-like with zero average. In this work we characterized the singularities of random walks constructed from point processes and used the so-called *Mexican hat* wavelet which is the second derivative of a Gaussian function:

$$\psi(\tau) = \frac{\mathrm{d}^2}{\mathrm{d}\tau^2}\left[\exp\left(-\frac{\tau^2}{2}\right)\right]. \quad (2)$$

A local singular behavior of $f(x)$ at the point x_0 results in an increase of $|T_\psi[f](x,a)|$ as $x \to x_0$ and can be characterized by the Hölder exponent $h(x_0)$ that quantifies the scaling of the wavelet coefficients for small a: $T_\psi[f](x_0,a) \sim a^{h(x_0)}$.

Further, the statistical description of local singularities is performed using the notion of the *partition function* $Z(q,a)$ [8] being the sum of qth powers of the local maxima of $|T_\psi[f](x,a)|$ at the scale a [15]. For small values of a the following power-law behavior is expected [8]:

$$Z(q,a) \sim a^{\tau(q)}, \quad (3)$$

with the scaling exponents $\tau(q)$. The variation with powers q allows us to obtain a linear dependence $\tau(q)$ with the single Hölder exponent $h(q) = \mathrm{d}\tau(q)/\mathrm{d}q = const$ in the case of monofractal objects and a nonlinear function with a large number of exponents $h(q)$ for multifractals. The singularity spectrum $D(h)$ can thereafter easily be estimated using the Legendre transform:

$$D(h) = qh - \tau(q). \quad (4)$$

For positive values of q the partition function $Z(q,a)$ characterizes the scaling of large fluctuations in the data series (strong singularities); for negative q it reflects the scaling of small fluctuations (weak singularities). Application of the WTMM-approach to time series allows us to characterize correlations of different types if $h \neq 0.5$ and $D(h) \neq 0$. In particular, the range $0 < h < 0.5$ implies the presence of anti-correlated behavior. This means that large (compared to the average) values of the data series are more probably to be followed by small values and vice versa [4]. $h > 0.5$ reflects correlated dynamics where large values are more likely to be followed by large values, and $h = 0.5$ corresponds to uncorrelated behavior [12].

4. Results

Application of multifractal concept to an analysis of point processes extracted from the BP signals has revealed differences in the stress-induced reactions of male and female rats. As a whole, males demonstrated significantly stronger changes of the singularity spectrum $D(h)$ at stress concerning a resting state. In Fig. 2 results for two rats are presented (male and female) that show perhaps the clearest, but at the same time typical enough distinctions in responses to stress. We can see that numerical values of the Hölder exponent $h(q)$ decrease at stress for male (Fig. 2a and b). Reduction of the given exponents indicates a change of correlation; the point process being analyzed becomes less "smooth". Such a variation of scaling characteristics can be quantified by the difference in the values h for $q = 0$ related to the maxima of $D(h)$-spectra. Because the fractal dimensions D are close to 1 if $q = 0$, we need to know only the Hölder exponents $h(q)$ to characterize the location of singularity spectrum as well as the degree of multifractality. (For this purpose it is easy to introduce some measure of multiscality Δh being a range of possible values $h(q)$). Let's note, that there is some reduction of the given measure in Fig. 2a and b apart from a change of correlation properties: $\Delta h \approx 0.5$ corresponds to a resting state whereas $\Delta h \approx 0.3$ corresponds to stress. In other words, the singularity spectrum $D(h)$ becomes narrower at stress, however, the analyzed data remain a multifractal process at all stages. Another response is observed for female.

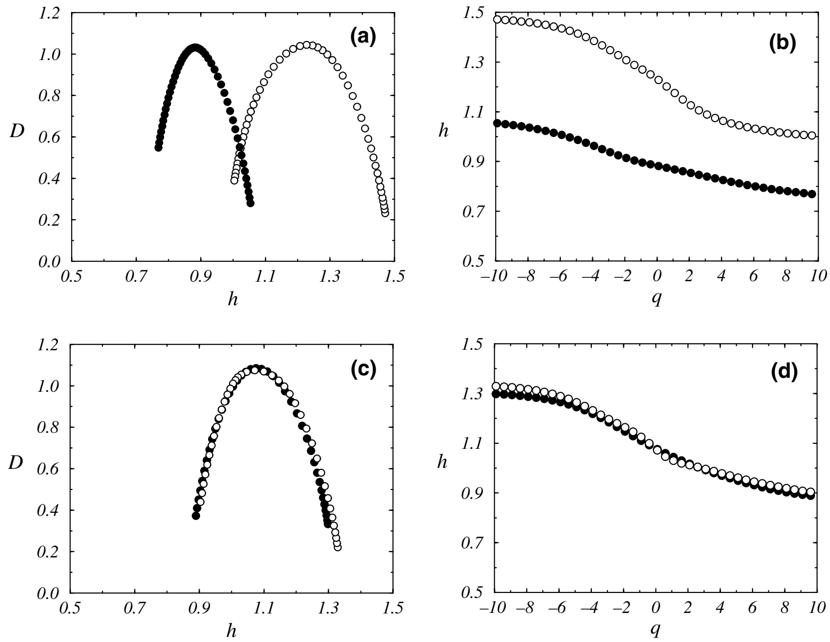

Fig. 2. Singularity spectra $D(h)$ and the Hölder exponents estimated from point processes that characterize BP dynamics of a male (a and b) and a female (c and d) rat. White circles correspond to a resting state, and black circles correspond to a stress condition.

According to Fig. 2c and d, neither changes of $h(q)$, nor decreasing of multiscality take place. The discussed characteristics remain practically constant in the course of experiments. We can conclude, therefore, that the blood pressure dynamics of this rat was insensitive to stress (at least, from the viewpoint of its multifractal description).

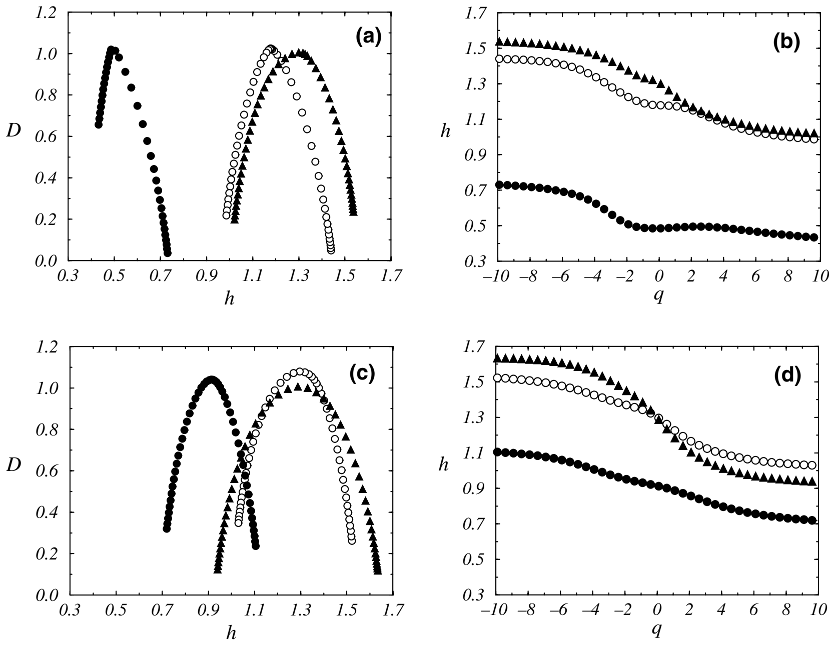

Fig. 3. Typical enough phenomena in multifractal characterization of blood pressure dynamics in male rats. We show here the results related to a resting state (white circles), to stress (black circles) and to recovery process (black triangles).

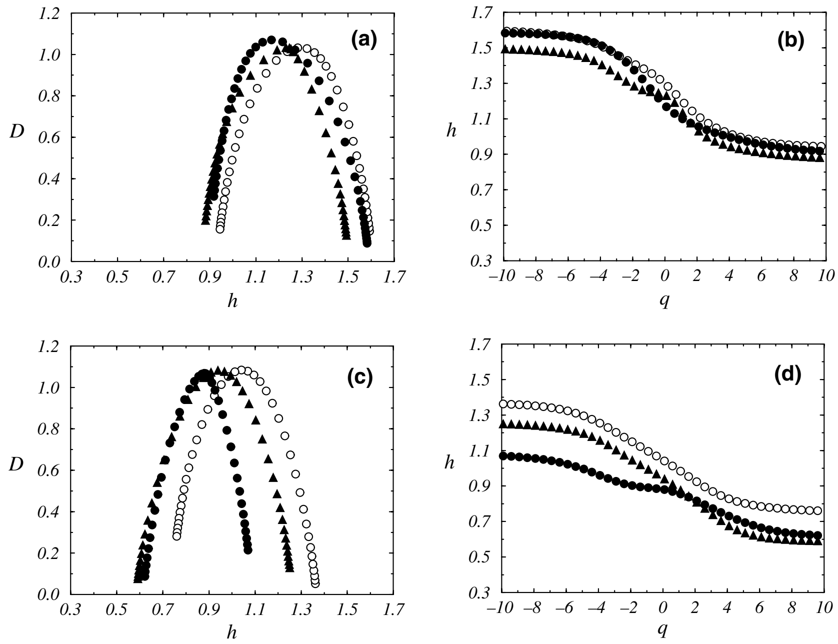

Fig. 4. Typical enough phenomena in multifractal characterization of blood pressure dynamics in female rats. All denotations are the same as in Fig. 3.

Consider some additional illustrations. Figs. 3 and 4 demonstrate the main characteristics of multifractal formalism for other male and female rats, respectively. Here we show the singularity spectra $D(h)$ and the spectra of Hölder exponents $h(q)$ for all stages of experiments including a recovery process that is a transition to a resting state after the termination of stress. We can see that the above mentioned effects are qualitatively the same. Again, males display rather strong changes of multifractality at stress whereas females do not demonstrate essential changes of their blood pressure dynamics. In both Figures, the singularity spectra related to recovery processes are quite similar to the initial $D(h)$-spectra that were observed up to stress.

Aiming to show typicalness of the discussed phenomena, we would like to present results of the statistical analysis.

(1) *Male rats*. As a rule, numerical values of the Hölder exponents decreased at stress relative to a resting state (such an effect was observed for 9 rats from 10). Moreover, 7 rats demonstrated essential distinctions between locations of the singularity spectra. Having denoted the values $h(0)$ estimated in rest and at stress by $h^r(0)$ and $h^s(0)$, respectively, it is possible to quantify stress-induced effects. For 7 rats the following difference is obtained: $h^r(0) - h^s(0) \geqslant 0.3$ (we diagnose this case as strong changes). For other 2 rats the given phenomenon was less expressed: $h^r(0) - h^s(0) \in [0.1 - 0.2]$. Only for 1 rat from 10, the exponents $h(q)$ increased at stress (atypical reaction).

Reduction of the multiscality degree Δh was observed for 6 male rats. Using similar denotations $\Delta h^r(0)$ and $\Delta h^s(0)$, this reduction can be quantitatively described as follows: $\Delta h^r(0) - \Delta h^s(0) \in [0.15 - 0.4]$. For other rats the measure of multiscality did not show clear changes: $\Delta h^s(0) \approx \Delta h^r(0)$.

(2) *Female rats*. Usually, females demonstrated only small decreasing of the Hölder exponents: $h^r(0) - h^s(0) < 0.15$ (6 rats from 8). For 2 rats the exponents increased, namely: $h^s(0) - h^r(0) \in [0.1 - 0.2]$. We have not found rats who display strong changes of the location of $D(h)$-spectrum. Multifractality degree Δh did not show essential changes for 5 females. In one case Δh clearly decreased: $\Delta h^r(0) - \Delta h^s(0) \approx 0.35$. For the remaining 2 rats it increased: $\Delta h^s(0) - \Delta h^r(0) \approx 0.2$.

Finally, we would like to mention some seldom encountered phenomena. In particular, for one rat we have found a transition from a multifractal to a monofractal structure of point processes, the latter means that stress can sometimes lead to a loss of multifractality in the cardiovascular dynamics. However, such phenomenon is atypical: for all other rats the BP dynamics displayed multifractal properties throughout the experimental signals. In one case a clear transition from correlated ($h > 0.5$ at a resting state) to uncorrelated behaviour ($h \approx 0.5$ at stress) was observed. It should be noted that such effect is also related to seldom encountered ones. More typical situation consists in the presence of correlations at all stages.

5. Conclusions

In this paper, we studied the possibility of a multifractal characterization of blood pressure dynamics in healthy rats. Taking sequences of time intervals between the local maxima of BP signals, we analyzed how stress-induced changes of a cardiovascular dynamics are reflected in the structure of the given point processes. The main results of this study consists in the following.

Reaction to stress may be different for male and female rats although there are some general effects. In our experiments, for 15 from 18 rats the Hölder exponents estimated from point processes decreased at stress (or, in few cases they were practically constant at all stages). The latter allows to conclude that stress typically results in a change of correlation properties: the analyzed data become less "smooth". Reduction of the multiscality degree was found for 7 rats; for 9 rats the measure Δh was unchanged, i.e. stress do not increase complexity of the BP dynamics.

As a rule, male rats show a strong enough reduction of the Hölder exponents at stress that is accompanied by a reduction of multifractality for about a half of them. Females usually demonstrate a small decreasing of the Hölder exponents without a change of the multiscality degree. The obtained results testify that the wavelet based multifractal formalism represents a really promising tool for data processing: it can be successfully applied for classification of a state of biological objects from highly nonstationary signals. This tool allows to characterize in details various changes of the complex evolutionary dynamics of living systems.

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