Biocybernetics and Biomedical Engineering
2012, Volume 32, Number 1, pp. 17–26

Multifractal Analysis of Laser Doppler Flowmetry Signals: Partition Function and Generalized Dimensions of Data Recorded before and after Local Heating

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Laser Doppler flowmetry (LDF) signals – that reflect the peripheral *cardiovascular* system – are now widespread in blood microcirculation research. Over the last few years, the *central* cardiovascular system has been the subject of many fractal and multifractal works. However, only very few multifractal studies of LDF signals have been published. Such multifractal analyses have shown that LDF data can be weakly multifractal but the origin of such characteristics are still unknown. We therefore herein propose a multifractal analysis of LDF signals recorded on the forearm of twelve healthy subjects, before and after skin local heating. The results show that the partition functions for all the signals have power-law characteristics. Moreover, generalized dimensions present very few variations with q for the signals recorded before heating; these variations are larger 20 minutes after local heating. Physiological activities may therefore play a role in the weak multifractal properties of LDF data.

K e y w o r d s: generalized dimensions, laser Doppler flowmetry, local heating, microcirculation, multifractal analysis, partition function

1. Introduction

Laser Doppler flowmetry (LDF) is now widespread in blood microcirculation research dedicated to physiology. This technique relies on the Doppler effect generated by the interaction between moving blood cells – mainly red blood cells – of the micro-

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Received 04 March 2011; accepted 03 October 2011

circulation, and photons which are led via an optical fiber from a laser unit towards the tissue (skin) under study. However, due to large regional differences in the skin microcirculatory system and to its adaptability to hemodynamics changeable conditions, LDF signals possess spatial and temporal fluctuations reflecting the *peripheral* cardiovascular system adaptations.

Over the last few years, the *central* cardiovascular system has been the subject of many fractal and multifractal studies, mainly for data characterization and classification. Fractal signals are considered as self-similar. Therefore, a subset of these signals, when magnified to the size of the whole, is indistinguishable from the whole [1]. We can thus define one scaling exponent to completely describe the dynamics of the process. The need for more than one scaling exponent indicates that the process is not monofractal but could be multifractal. A multifractal signal is therefore seen as more complex than a monofractal signal: the dilatation factor needed to be able to distinguish the detail from the whole signal depends on the detail being observed. A set of fractal dimensions is thus needed to describe the scaling properties.

Several works have been performed in order to analyze the possible monofractal characteristics of LDF signals (see for example Refs. [2–7]). However, to the best of our knowledge, only very few multifractal studies of LDF signals have been published [8–12]. Such multifractal analyses have shown that LDF data can be weakly multifractal. However, the origin of such characteristics is still unknown. Do they come from the optical speckle, from the underlying physiological activities, from the complexity of the blood flow in the microvascular vessels...?

In order to bring information on this question, we herein propose a multifractal analysis of LDF signals through the specific analysis of their partition function and generalized dimensions. The signals processed are recorded on the forearm of healthy subjects, before and after local heating to 44°C. Such a local heating leads to a maximum vasodilation in skin [13] due to axon-reflex- and nitric oxide-dependent mechanisms [14–17]. Our goal is to analyze and discuss if the physiological phenomena induced by local heating may modify the partition function and generalized dimensions for the LDF recordings.

2. Laser Doppler Flowmetry Technique

Laser Doppler flowmetry (LDF) is a non invasive method enabling the monitoring of microvascular blood flow. This technique is easy to use and has supplemented other methods that have been presented in detail in the literature (photoelectric plethysmography, video-photometric capillaroscopy, thermal and radioisotope clearance, orthogonal polarization spectral imaging). Clinical applications of the LDF are related to diabetes microangiopathy, peripheral vascular diseases, Raynaud's phenomenon, pharmacological applications, thermal injury, plastic surgery, flap surveillance, skin diseases, ... see for example Refs. [18–21]. LDF measurements from the skin reflect

perfusion in capillaries, arterioles, venules, and dermal vascular plexa [22–24]. The perfusion through capillaries refers to the nutritive flow, whereas flow through arterioles, venules and shunting vessels refers to the temperature regulation flow, and also feed and drain the capillary network.

LDF systems can be divided into two categories: the laser Doppler perfusion monitors and the laser Doppler perfusion imagers. The LDF technique relies on the Doppler effect. Thus, when a coherent light is directed toward a tissue, photons are scattered by moving objects and by static structures. If these photons encounter moving particles, the Doppler effect appears. The photon frequency is therefore modified. When the reemitted light is directed toward a photodetector, optical mixing of light with shifted and non shifted frequency gives rise to a stochastic photocurrent. Power spectrum $P(x)$ of this photocurrent is linked to the blood cells properties present in the illuminated volume. More precisely, when concentration of the moving red blood cells is low, the first moment $\int \omega P(\omega) d\omega$ scales with concentration of the moving blood cells times their average velocity, whereas $\int P(\omega) d\omega$ scales with concentration of the moving blood cells (see for example Ref. [25]). The LDF probe used for skin perfusion evaluation with laser Doppler perfusion monitors is usually a fiber optic probe having generally 0.25 mm between the transmitting and receiving fibers. This leads to a sampling depth on the order of 1 mm for human skin.

3. Multifractal Analysis Principles

Complex processes from various natural systems, as the ones found in biology or medicine, are often characterized by inhomogeneity, a feature that may be described by scaling properties. The existence of power-laws (scaling) indicates the presence of fractal behaviour. Monofractals are homogeneous, in the sense that they have the same scaling properties characterized by a single singularity exponent. However, a multifractal signal cannot be characterized by a single power law exponent. It requires many fractal dimensions.

The computation of generalized dimensions through determination of a partition function can be performed with box-counting techniques [26]. In these techniques, the signal under study is meshed with various box sizes ε and a normalized measure is computed in each box. We herein computed the generalized dimensions of LDF signals with a box counting approach. Thus, for the processing steps, each signal was first normalized to 75 a.u. (in order to remove the amplitude effects in the multifractal analysis), and then divided by the sum of its samples in order to obtain a measure. Afterwards, the measure was partitioned into boxes of size ε.
The so-called partition function $Z(q,\varepsilon)$ is defined as [27]

$$Z(q,\varepsilon) = \sum_{i=1}^{N_{boxes(\varepsilon)}} \mu_i(\varepsilon)^q \tag{1}$$

where $\mu_i(\varepsilon)$ is probability of finding a point in the ith box of size ε covering the measure and $N_{boxes}(\varepsilon)$ indicates the number of boxes of size ε needed to cover the measure. The exponent q is a real parameter that indicates the order of the moment of the measure. High values of q enhance boxes with relatively high values for $\mu_i(\varepsilon)$ (if $\mu_i > \mu_j$, and if $q >> 0$, then $\mu_i^q >> \mu_j^q$), while low values of q favor boxes with relatively low values of $\mu_i(\varepsilon)$. Moreover, the size ε of the boxes can be seen as a filter: large box is equivalent to apply a large scale filter to the map. Changing the size ε leads to explorations at different scales.

The generalized dimensions are then given by

$$D_q = \frac{1}{q\text{-}1} \lim_{\varepsilon \to 0} \frac{\ln Z(q,\varepsilon)}{\ln \varepsilon} \quad (q \neq 1), \tag{2}$$

$$D_1 = \lim_{\varepsilon \to 0} \frac{\sum_i \mu_i \log \mu_i}{\log \varepsilon}. \tag{3}$$

D_0 is the capacity dimension, D_1 is the information dimension, and D_2 corresponds to the correlation dimension which is a measure of correlation between pairs of points inside a box. For $q = 3, 4, \ldots$, one can define a set of generalized dimensions $D_3, D_4, \ldots$ associated with higher-order correlations between triples, quadruples, ... of points in each box. For a given value of q, $Z(q,\varepsilon)$ is computed for different values of ε, and D_q is estimated from the plot of $\log Z(q,\varepsilon)$ against $\log \varepsilon$. Multifractality means a non-uniform fractal. If D_q is constant for all values of q, the signal is considered as monofractal. Otherwise, it is called multifractal. The greater the difference between D_0 and the other dimensions D_q, the more non-uniform is the signal.

4. Multifractal Analysis of Laser Doppler Flowmetry Signals

4.1. Measurement Procedure

Twelve healthy subjects (6 men, 6 women; mean age: 29.5 ± 7.1) participated in the study. Each of the subjects gave his / her written informed consent to participate. None of the subject had known cardiovascular disease. For the signal acquisitions, the subjects were placed supine in a quiet room at ambient temperature of 24 ± 1°C. For the measurement procedure, a laser Doppler probe (probe 481, Perimed, Stockholm, Sweden) was positioned on the ventral face of the right forearm of the subject. This probe was connected to a laser Doppler flowmeter (Periflux system 5000, Perimed, Stockholm, Sweden) and to a temperature unit (PF5020 TempUnit, Perimed, Stockholm, Sweden) to perform local heating. Skin blood flow was assessed in arbitrary units (a.u.) and recorded on a computer via an analog-to-digital converter (Biopac System) with sampling frequency of 20 Hz. The LDF signals were recorded

for at least 5 minutes before the temperature unit was switched on (the heating temperature was set to 44°C). The local heating was performed for at least 25 minutes while the signal recordings continued. After acquisitions, two segments of signals were taken into account for post-processing purposes for each subject: 2^{12} samples of data recorded before local heating and 2^{12} samples of data recorded 20 minutes after local heating to 44°C.

4.2. Partition Function and Generalized Dimensions Computation

For the experimental signals, the limit found in Equation 2 cannot be computed. This is due either because no information at very small scales is available (due to the sampling of the signal), or because below a minimum physical length no scaling can exist at all. That is why a scaling region is chosen where a power-law can be fitted to the partition function. In our work, the D_q curve has been obtained by fitting the power-law to the partition function in the range of scales $1 \leq \varepsilon \leq 3$ samples. This corresponds to times between 0.05 s and 0.15 s. Moreover, we have chosen the q range equal to [−3, 3]. Such a small range prevents the predominance role that could be played by outlier samples in the signal.

5. Results and Discussion

Two normalized LDF signals, one recorded before heating and the other after 20 minutes of local heating, are presented in Fig. 1. For each LDF signal, we have computed the partition function $Z(q,\varepsilon)$ and estimated the generalized dimensions D_q as mentioned above. The partition functions and the corresponding-evaluated generalized dimensions for the LDF signals recorded before and after local heating are shown in Figs 2, 3, and 4a. For the parameters given above and for the amplitude normalization of the signals to 75 a.u., our results show that the partition functions for all our signals present power-law characteristics, for all scales (see examples in Figs 2 and 3). Moreover, we can observe that the generalized dimensions present very few variations with q for the signals recorded before heating, while these variations are larger for the signals recorded after 20 minutes of local heating (see Fig. 4a). This is true for our twelve subjects. Thus, for the examples shown in Fig. 4a, we can observe that the evaluated generalized dimensions are equal to 1 for the signal recorded before local heating, when q varies from –3 to 3. However, they go from 0.996 to 1.005 for the recording performed after 20 minutes of local heating, for the same range of q. The higher variations of the generalized dimensions D_q when increasing q for the LDF signals recorded after local heating suggest that the physiological activities generated by local heating may play a role in the multifractal characteristics of LDF data.

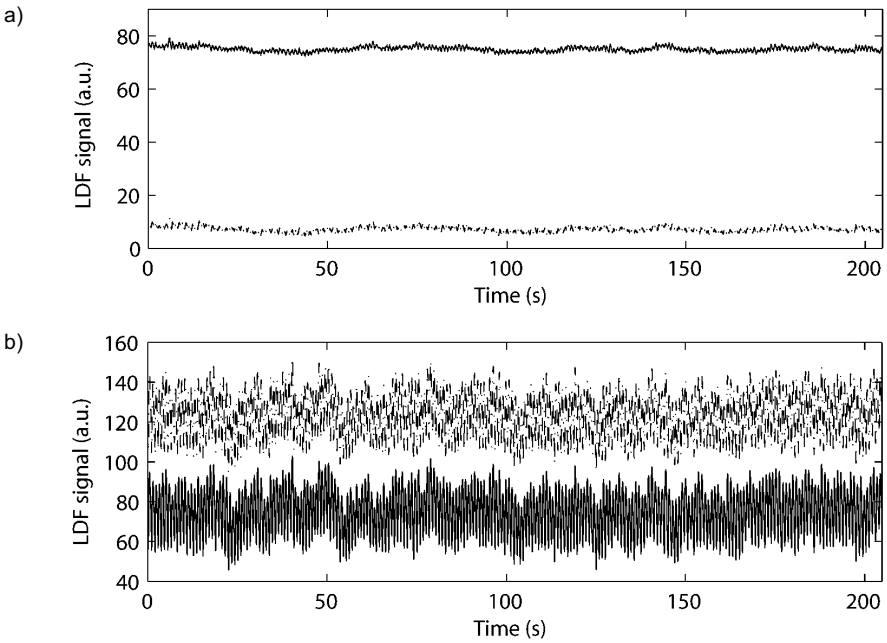

Fig. 1. LDF signal recorded on the forearm of a healthy subject a) before local heating; b) after 20 minutes of local heating to 44ºC. The dotted lines correspond to the signals before amplitude normalization to 75 a.u.; the solid lines correspond to the signals after amplitude normalization to 75 a.u

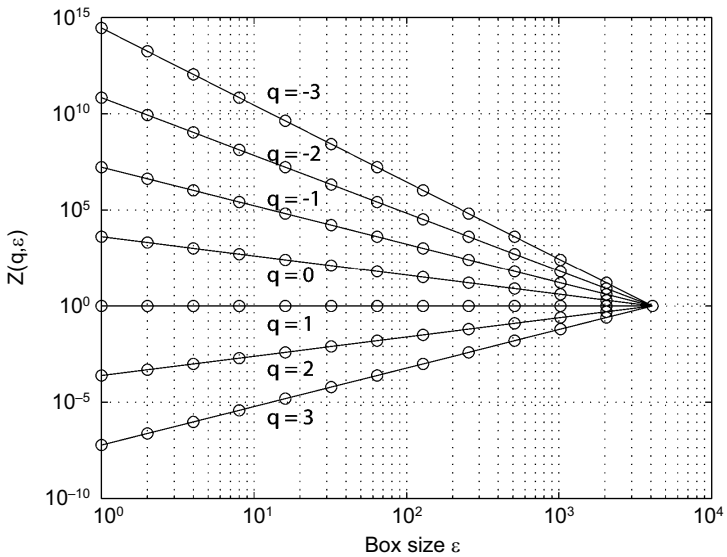

Fig. 2. Partition function of a LDF signal recorded on the forearm of a healthy subject before local heating (see normalized signal shown in Fig. 1a)

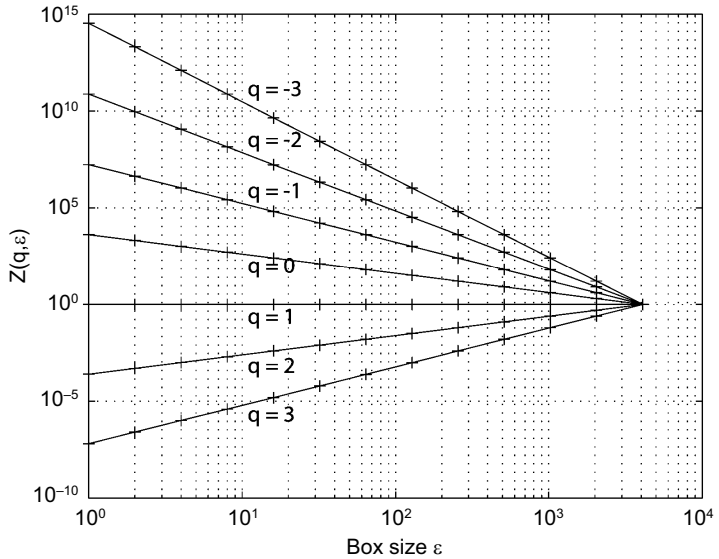

Fig. 3. Partition function of a LDF signal recorded on the forearm of a healthy subject after 20 minutes of local heating to 44ºC (see normalized signal shown in Fig. 1b)

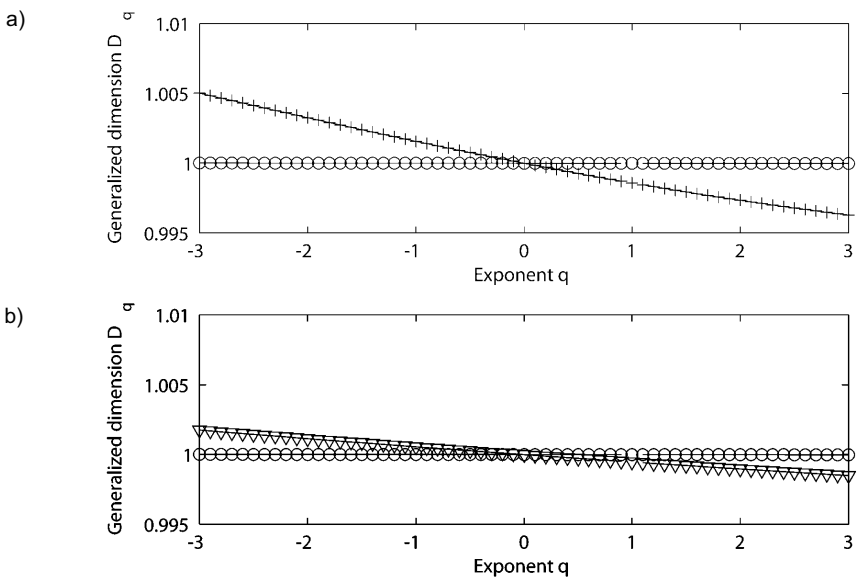

Fig. 4. a) Generalized dimensions of a LDF signal recorded on the forearm of a healthy subject before local heating (circle curve) and after 20 minutes of local heating to 44ºC ('+' curve) (see normalized signals shown in Fig. 1). b) Generalized dimensions of a LDF signal recorded on the forearm of a healthy subject before local heating (see signal presented in Fig. 1a), before (triangle curve) and after (circle curve) amplitude normalization to 75 a.u.

We note that the D_q variations when increasing q are rather low, but are in the same range as those found for other biomedical signals or cosmic microwave background maps (see for example Refs. [28] and [29]). As mentioned above, the higher the mean value of a given signal, the lower its D_q variations (see part 3). Therefore, the generalized dimensions of the signal presented in Fig. 1a show less variations than those that would be obtained before amplitude normalization to 75 a.u., because such normalization leads to an increase in the signal mean value (see Figs 1 and 4b). Our goal herein was to compare the variations of the generalized dimensions of LDF signals before and after local heating, in order to analyze if the physiological activities generated by local heating may play a role in the multifractal behaviour of the signals. A normalization of the amplitudes was therefore needed. The latter shows that the generalized dimensions show more variations after than before heating.

From our results, we may deduce that some of the physiological activities coming into account during local heating – namely axon-reflex- and/or nitric oxide-dependent mechanisms – may lead to an increase in the possible multifractal properties of LDF signals. However, other studies in this field are needed in order to confirm the hypothesis. Moreover, the analysis proposed herein relies, among others, on the size of the boxes chosen for the estimation of the generalized dimensions (see the limit in Equation 2). For the experimental signals, as those processed in our work, we still do not know which scales would have to be taken into account for such estimations. Further work is therefore needed in order to find the corresponding answers.

6. Conclusion

In order to bring information on the weak multifractal properties of LDF signal, we herein proposed a multifractal analysis of LDF signals recorded on the forearm of twelve healthy subjects, before and after skin local heating to 44°C. Such a local heating leads to maximal vasodilation due to axon-reflex- and nitric oxide-dependent mechanisms. Our multifractal analysis is led through the specific analysis of signals' partition function and generalized dimensions. The results show that the partition functions for all the signals have power-law characteristics. Moreover, we can observe that the generalized dimensions present very few variations with q for the signals recorded before heating, while these variations are larger for all signals recorded after 20 minutes of local heating. The higher variations of the generalized dimensions D_q when increasing q for the LDF signals recorded after local heating suggest that the corresponding data may present stronger multifractal characteristics than these corresponding to the signals recorded before heating. Physiological activities may therefore play a role in the weak multifractal properties of LDF data.

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