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Analysis of RR intervals time series of congestive heart failure patients with Higuchi's fractal dimension

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Abstract—**We study time series of RR intervals of subjects with normal sinus rhythm (NSR) during sleep and wake phases and we also analyze time series of subjects with congestive heart failure (CHF) in both phases with the method of Higuchi`s fractal dimension. We have found the presence of oscillations in the plots we have used to evaluate the Higuchi's fractal dimension; these oscillations seem to be associated with the appearance of periodicities in the time series of CHF patients in the sleep phase. These periodicities do not appear in all the six hours of the sleep phase, so this regular behavior is not observed in all sleep stages. It could be possible that patients that always show these periodicities are in worst condition, and it is possible that the disease worsens when periodicities appear in the Higuchi's graph.**

I. INTRODUCTION

RECENTLY, there has been a lot of research involving the analysis of heart rate variability (HRV) by using the methods of nonlinear dynamics. For instance, the detrended fluctuation analysis (DFA) method [1, 2] has been used to show that there are differences in the long-range scaling of HRV between healthy and unhealthy subjects [3-5] and young and elderly persons [6-7]. The Higuchi's fractal dimension method [8-9] has been used for the same task [4, 6, 10]. In last years, multifractal analysis has begun to be used for the study of physiological time series [11-16]. Ivanov et al. [12] have established the relevance of the multifractal formalism for the description of a physiological signal.

In a past work [17], we applied the DFA method, the Higuchi's method and multifractal analysis [18, 19] to study time series of RR intervals of subjects with NSR and CHF patients, during sleep and wake phases, in order to characterize the type of correlations in each time series. Sleep-wake differences in scaling behavior of the human heartbeat was also studied by Ivanov et al. [20], they found by using DFA, different correlation degree in heartbeat fluctuations during sleep compared to wake periods in both healthy subjects and heart failure patients.

We applied the DFA method to the time series of NSR subjects, with 6h-segments of both sleep and wake phases and, although for some subjects there are differences between the γ-values (the DFA-exponent), in the average, we found no significant differences between the γ-values in the sleep and wake phases. We mentioned in that work [17], that the obtained results seemed to be in agreement with the results of Alvarez-Ramírez et al. [21] but not with the results of Ivanov et al. [12]. We also calculated the correlations in both wake and sleep phases with the Higuchi's method, and we obtained different significant values (although they were close). We thought that the differences between our results and the Alvarez- Ramírez results could be explained by the presence of crossovers in the dynamics of correlations (the crossover is a breakdown in some statistical measure of the time series, such as Higuchi's fractal dimension, DFA exponent or the spectral exponent [4-5, 7].

We have also found that the average width of the multifractal spectra for wake and sleep segments of healthy persons have not significant difference and the result for the congestive databases is the same, it means that the width of the average multifractal spectra of the wake and sleep segments of CHF subjects also do not have significant differences. This fact seemed to be surprising, but we have proposed the analysis of the multifractal spectrum symmetry as an additional tool to characterize (and differentiate) the spectra [16]. The spectra of CHF patients lose multifractality and complexity. We postulated that this is associated with the appearance of periodic components in the 6h segments time series of RR intervals in the CHF patients, and this fact can be seen in the plot we use to calculate the Higuchi fractal dimension, this fact is very important because we did not find these oscillations in healthy persons in neither of the two phases, in the CHF patients they are encountered in the sleep phase of many patients and hardly ever in the wake phase.

In this work we do a further analysis of these 6h-segments of the CHF patients in the sleep phase, we separated in segment of 1 hour in order to show if these periodical components are present in all the sleep phase or only in some sleep stages, and we have encountered interesting results: some patients show these periodicities in all the six segments of 1 h, and the majority show these periodicities only in one, two or three segments of one hour, we think that this fact could be related with the severity of the disease, as it will be discussed further on.

II. THE HIGUCHI'S METHOD

The fractal dimension of self-similar objects in the plane is defined in terms of the isotropic distribution of its parts, which can be scaled by only a scaling factor. This property changes in the case of self-affine fractals because its spatial distribution is not isotropic and the scaling factor is different

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for each direction. Higuchi [8, 9] proposed one method to calculate the fractal dimension of self-affine curves in terms of the slope of the straight line that fits the curve length versus the time interval (the lag) in a log-log graph. The method consists of considering a finite set of data taken in a regular interval $v(1), v(2), v(3), \cdots, v(N)$. From this series we construct new series v_k^m, defined as

$$v_k^m : v(m), v(m+k), v(m+2k), v\left(m+\left[\frac{N-k}{k}\right]\cdot k\right) \quad (1)$$

With $m = 1,2,3, \ldots, k$, where [ ] denotes the Gauss notation for the integer part and k, m are integers that indicate the initial time and the time interval, respectively. For an interval time equal to k, they are obtained k new sets of time series. For instance, in the case of $k=3$ and $N=100$, the three series that are obtained with this process are: $v_1^3 : v(1), v(4), v(7), \cdots v(97)$
$v_3^2 : v(2), v(5), v(8), \ldots, v(98)$ $v_3^3 : v(3), v(6), v(9), \ldots, v(99)$.

The length of the curve v_k^m, is defined as:

$$L_m(k) = \frac{1}{k}\left[\left(\sum_{i=1}^{\left[\frac{N-m}{k}\right]} \left|v(m+ik) - v(m+(i-1)k)\right|\right)\frac{N-1}{\left[\frac{N-m}{k}\right]k}\right] \quad (2)$$

Where the term $(N-1)/[N-m/k]k$ is a normalization factor. Then, the curve longitude for the interval k, is $\langle L(k)\rangle$, the average over k sets $L_m(k)$. Finally, if $\langle L(k)\rangle \propto k^{-D}$, then there is a scaling relation, and the scaling exponent is D the Higuchi's fractal dimension. For auto-affine curves, this fractal dimension is related with the β exponent by means of $\beta = 5 - 2D$, if D is in the range $1<D<2$ then $1<\beta<3$ [8]. Higuchi showed that this method provides a precise estimation of the fractal dimension even for a small number of data. Higuchi developed its method as an alternative to spectral analysis because although there is a relation between D and β, the standard deviation of the spectral analysis when calculating the fractal dimension is greater than the fractal dimension obtained when calculating with the Higuchi's method. In addition, the Higuchi's method has allowed to define with clarity the two or more regions in which the graph of log $L_m(k)$ vs log k is divided in case of crossovers, that is to say, the points that divide different scaling regions with different values of the fractal dimension D [5, 7-9, 22].

III. HRV DATA

We take the HRV data from the public databases of Physionet [23]. The HRV data are signals derived from ECG recordings, which were made by using ambulatory ECG recorders with a typical recording bandwidth of the order of 0.1-40 Hz. Each data set includes recording over a period of 24h. Data for sleep phase were considered within the database as the six continuous hours of lowest heart average heart rate; waking hours were defined as the six continuous hours of highest heart rate. We do not analyze the series in which it was impossible to define this 6h-interval. The healthy cases were taken from the normal sinus rhythm RR interval database which contains 54 cases (aged 28-72 years) including male and female subjects, the unhealthy subjects were taken from the congestive heart failure RR interval database which contains 29 cases (only 25 cases analyzed) and other CHF data were taken from the BIDMC congestive heart failure database which contains 15 cases (12 cases analyzed). We changed wrong measures (artifacts) taking the average between the last and the following measure. And then we divided each 6h-segment in segments of one hour, we analyzed this 1h-segments for the sleep and wake phases but as we have mentioned earlier, the most interesting results were encountered in the sleep phase.

IV. RESULTS

When we analyzed the RR interval time series of healthy subjects with the Higuchi's method in the sleep phase, there are no oscillations, but when we applied this method to the series of the CHF patients we observe oscillations.

In the Higuchi's plot we have showed that these oscillations are associated with periodicities in the time series, we think this fact is very important because we did not find these oscillations in healthy persons in neither of the two phases, in the CHF patients they are encountered in the sleep phase of many patients and hardly ever in the wake phase.

Our results show that this appearance of periodic components can be observed in the graph that is used to calculate the Higuchi's fractal dimension. This can be shown generating a time series of known fractal dimension, after this we add this time series several periodic components and upon calculating the Higuchi's graph we observe oscillations, we can calculate the frequencies of these oscillations and they correspond precisely to the periodic components that we added (Figure 1).

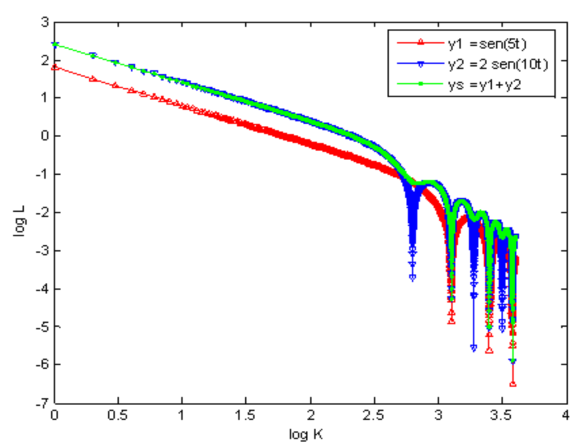

Fig.1 Demonstration of the appearance of regularities from a series with Higuchi's dimension D, periodic components are added whose frequencies are obtained from the graph and these frequencies are equal to the frequencies of the periodic components that were added.

To make more evident what happens in this part of the Higuchi's graph we show in Figure 2 the amplified part that corresponds to these oscillations for a time series of a CHF patient once we have eliminated the trend. We observe in the case of the CHF patient (bellow) periodicities that definitely are not observed in the time series of a healthy person (above).

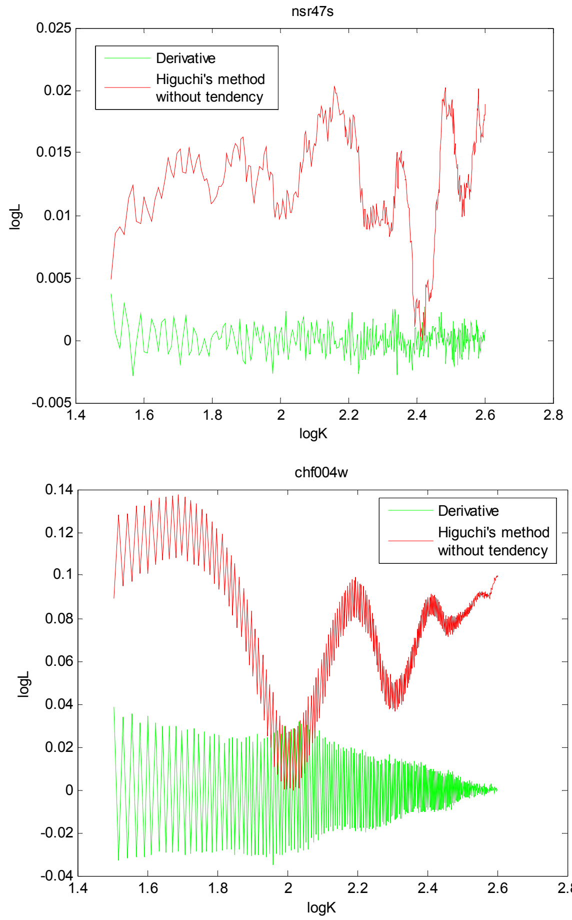

Fig. 2 Higuchi's method without tendency permits to show the appearance of regularities more accurately. Although in this case the derivative does not provide enough information, it does for other cases. Above: The method of Higuchi for healthy persons, we observe only small random variations. Bellow. Higuchi's method for a patient with congestive heart failure, we observe regular variations that in most cases show a periodic behavior.

The time series of the 1h-segments have the behavior we show in Figure 3 for healthy subjects and in Figure 4 for CHF patients in the sleep phase. In the last part of the graph of Figure 3 we eliminate the trend and we do not observe periodicities in the graph, but when we observe the behavior of the six 1h-segments for a CHF patient we observe periodicities in each one of the segments. We observe in Figure 5 the most common case, these periodicities are observed for all CHF patients in the sleep phase but only in one, two or three hours. We have established [17] that these periodicities are related to the disease, we think that when the periodicities are more accentuated the healthy state of the patient is worst, so we think that two hypothesis are plausible.

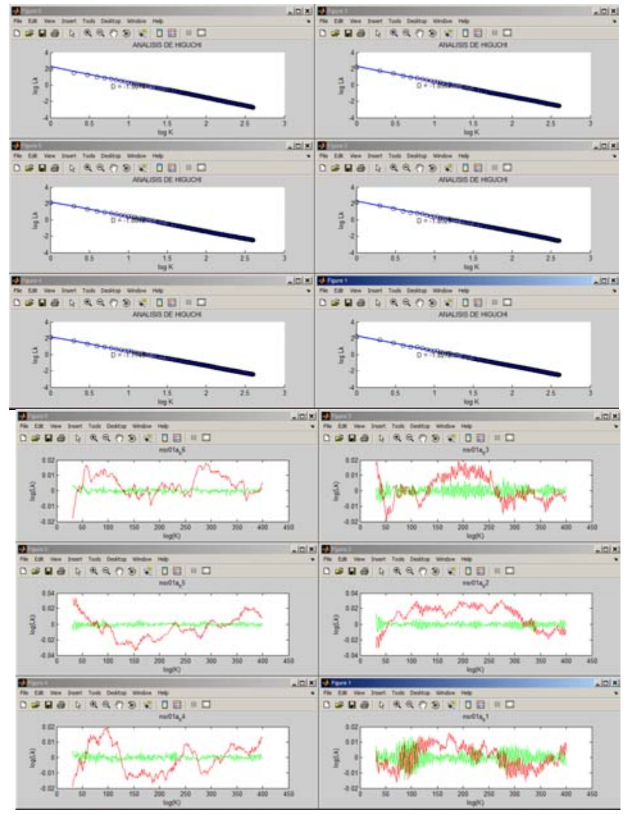

Fig. 3 Higuchi's method, for the six RR time series of 1 hour of a healthy person in the sleep phase, we take the last part of the Higuchi's plot and eliminate the trend, and in the resulting graph we do not observe any regular behavior. In green we show the first derivative that also is not regular.

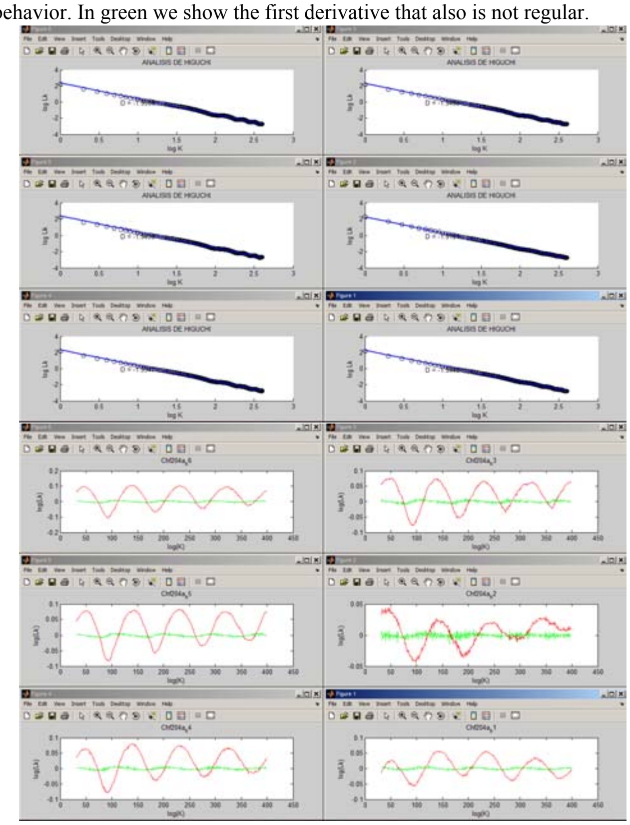

Fig. 4 Results of the Higuchi's method, for the six RR time series of 1 hour, for a CHF patient in the sleep phase, we can observe the presence of periodicities in each one of the six hours. The first derivative (in green) shows regularity too.

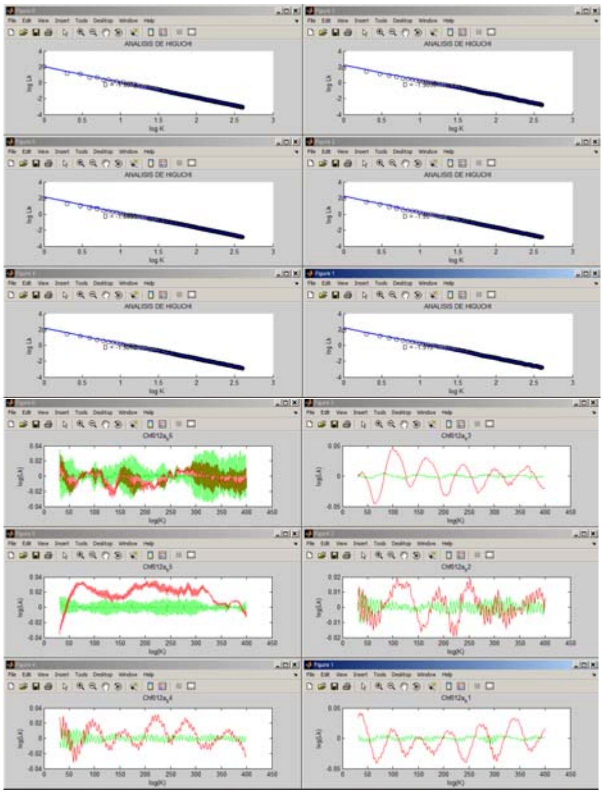

Fig. 5 The most common case, periodicities are not observed in all the six hours o f the sleep phase.

First, if the patient always shows periodicities the damage is more severe, and second, many times the patient does not show periodicities, the Higuchi's graph behavior is similar to the healthy Higuchi's graph, so it is possible that when the situation of the patient gets worse periodicities appear. However, more research is needed in order to confirm this hypothesis.

V. CONCLUSIONS

We have found the presence of oscillations in the plots we have used to evaluate the Higuchi's fractal dimension in the time series of CHF patients in the sleep phase. But when we observe the Higuchi's graph we observe that these periodicities do not appear in all the six hours of the sleep phase, so this regular behavior is not observed in all sleep stages. However, it seems that it is possible to say that in patients that always shows these periodicities the damage is more severe, and it seems to be that the patient gets worse when periodicities appear in the Higuchi's graph, but we have to admit that more research is needed for more conclusive results. For brevity, we only include qualitative results, but a complete statistical analysis is in progress.

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