Study on the Optimal Use of Generalized Hurst Exponents for Noninvasive Estimation of Atrial Fibrillation Organization

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Abstract

The Generalized Hurst Exponent $H(q)$ relates to the existence of long-term self-dependencies in the autocorrelation function of a time series. In the present work the optimal use of $H(q = 2)$ in the study of Atrial Fibrillation (AF) organization from noninvasive ECG recordings has been determined. With this aim, 60 signals from the Physionet AF Termination Database were studied.

First, the optimal data length for computing $H(2)$ was determined. Next, the application of a previous band-pass filtering step was assessed in order to improve the metric's performance. This improvement is due to the reduction of noise and ventricular residua in the signal that could affect the performance of nonlinear metrics. Finally, the use of $H(2)$ in short recordings was studied analyzing only the last seconds of each recording.

The use of a previous band-pass filtering stage improved significantly the performance of the metric and a classification accuracy of 95% was reached. In addition, the same classification accuracy was obtained in the analysis of the last 15 seconds of each recording, showing that $H(2)$ can be applied in the study of short ECG recordings.

1. Introduction

The most common cardiac arrhythmia found in clinical practice is Atrial Fibrillation (AF) [1]. During AF, the electrical atrial activity becomes uncoordinated [1]. As a consequence, the atria are unable to pump blood effectively [1]. When the arrhythmia can terminate spontaneously it is denoted as paroxysmal AF [1].

AF organization can be defined as how repetitive is the atrial activity (AA) signal pattern [2]. Moreover, since AF organization correlates with the likelihood of spontaneous termination and the therapy outcome, the noninvasive estimation of AF organization can provide valuable clinical information [3].

Nonlinear metrics estimate the regularity of a time series. Within the context of biomedical signals, nonlinear indices allow to obtain information related to the underlying mechanisms of the physiological processes [4]. In the study of AF, the use of nonlinear metrics can provide an estimation of AF organization through the measurement of the regularity of the AA [3, 5].

Hurst Exponents [6] are related to the existence of long-term self-dependencies in a time series, with higher values indicating a more regular signal [6]. Moreover, Hurst Exponents have been proposed as an estimation of Ventricular Fibrillation organization [7]. The Generalized Hurst Exponents $H(q)$ [8] are a generalization of the approach proposed by Hurst based on the study of the statistical features of the signal. Hence, the use of the Generalized Hurst Exponents could provide information about the regularity of the atrial activation patterns during AF and therefore it might provide an estimation of AF organization.

The use of $H(q)$ in the study of AF organization from the surface ECG has been proposed in [5]. However, no guidelines exist for the use of this metric in the study of the atrial activity. Therefore, the aim of the present work is to determine the optimal use of $H(q)$ under this scenario. To achieve this goal, some computational parameters of $H(q)$ will be varied on a reference database which has been widely used in the study of AF organization events.

2. Materials

2.1. Database

The AF Termination Database available at Physionet [9] was analyzed. This database contains two-lead, 1 minute long ECG recordings of paroxysmal AF with different degrees of organization. 60 of these recordings were studied to determine the optimal use of $H(q)$. These signals are divided into two groups: group N (non-terminating) contains AF episodes which lasted at least 1 hour after the end of the recording and group T (immediately-terminating) contains ECG recordings which end 1 second before the spontaneous reversion to sinus rhythm occurs. A detailed description of this database can be found in [10]. Lead V1 was chosen for the analysis.

2.2. Preprocessing

In order to obtain better alignment in QRST subtraction the signals were upsampled to 1 kHz using a cubic spline interpolation method [11]. Then, the signals were preprocessed in order to improve the analysis. First, baseline wander was removed by a bidirectional high-pass filtering with 0.5 Hz cut-off frequency. Then, the signals were filtered using an eight order IRR Chebyshev low-pass filter with 70 Hz cut-off frequency to reduce high frequency noise. Finally, powerline interference was removed using an adaptive notch filter, which preserves the ECG spectral information [12]. Finally, the Atrial Activity was extracted by applying an adaptive QRST cancelation method described in [13].

3. Methods

3.1. Generalized Hurst exponents

The Generalized Hurst Exponents ($H(q)$) [8] are a generalization of the approach proposed by Hurst [6] for the analysis of complex and inhomogeneous time series having many regions with different scaling properties. $H(q)$ measure the existence of long-term statistical dependencies in the q-order moments of the amplitude increments [8]. For a stochastic variable $x(t)$ these q-order moments can be represented by [8]

$$K_q(\tau) = \frac{\langle |x(t+\tau) - x(t)|^q \rangle}{\langle |x(t)|^q \rangle}. \quad (1)$$

Denoting the time between observations as ν, $H(q)$ can be defined from $K_q(\tau)$ as [8]

$$K_q(\tau) \sim (\frac{\tau}{\nu})^{qH(q)}. \quad (2)$$

Due to the nonstationary and nonlinear nature of the physiological processes underlying AF [14], the use of $H(q)$ to estimate its organization seems appropriate [15]. The interpretation of $H(q)$ depends on the value of q. $H(2)$ is related to the behavior of the autocorrelation function and therefore it is associated with the power spectrum of the signal [16]. Thus, $H(2)$ was selected as a possible organization index for surface recordings of AF.

3.2. Parameter optimization

Since no guidelines exist for the use of $H(2)$ in the study of AF signals, the optimal use of this metric was studied. First, the optimal data length for calculating $H(2)$ was determined. For this purpose $H(2)$ was computed over all non-overlapping segments of the signals ranging from thirty seconds to one second and then the average value over the whole recording was obtained.

On the other hand previous works have evidenced that the performance of nonlinear indices in the estimation of AF organization can be affected by the presence of noise and ventricular residua in the extracted AA signal [17]. As a consequence, the use of a previous band-pass filtering stage has been also studied in order to reduce the effect of these nuisance signals.

Two different filters were proposed. Since the 3–9 Hz band contains most of the atrial activity signal power [18], the use of a 3 to 9 Hz band-pass filter was studied. Furthermore, the extraction of the Main Atrial Wave (MAW) by selective filtering was also analyzed because it has been demonstrated that the computation of the MAW regularity using nonlinear metrics can estimate AF organization very efficiently [17]. The MAW was extracted using a band-pass FIR filter with 3 Hz bandwith centered on the dominant atrial frequency (DAF) of each signal [17]. Both filters were designed with the Chebyshev approximation, a linear phase and a relative sidelobe attenuation of 40 dB.

In order to compare the performance of $H(2)$ in the original and filtered signals, this metric was computed over all non-overlapping optimal length segments of the recordings and then the average value was calculated.

Finally, the optimal recording length to compute $H(2)$ was determined analyzing a gap of the last seconds of the signals and using, as computational parameters, the optimal segment length (15s) together with the optimal filtering stage (MAW).

3.3. Statistical analysis

The classification thresholds, specificities and sensitivities in the discrimination between groups N and T were obtained from the receiver operating characteristic (ROC) curves. The closest point to 100% accuracy was chosen as optimum threshold. The area under the ROC curve (AROC), which represents the performance of the metric, was also computed. AROC varies between 0.5 and 1 and higher values represent a better performance. When several parameter values reached the highest accuracy value, the one corresponding to the highest value of AROC was selected as optimal.

4. Results

Table 1 shows the classification results obtained using different segment lengths. The best classification results were attained using segment lengths of 10 and 15 seconds. The segment length of 15 seconds presented the highest AROC value, and therefore it was selected as optimal computational length.

Regarding the use of a previous band-pass filtering. $H(2)$ was computed over all non-overlapping 15 seconds segments of the signals and then the average value of each

Table 1. Classification results of $H(2)$ computed over the AA signal using different segment lengths.

	Se	Sp	Acc	AROC
60 s	53.85%	82.35%	70.00%	0.6335
30 s	61.54%	73.53%	68.33%	0.6640
20 s	57.69%	79.41%	67.10%	0.6606
15 s	57.69%	82.35%	71.66%	0.6640
10 s	50.00%	88.24%	71.66%	0.6369
5 s	57.69%	79.41%	70.00%	0.6561
1 s	84.62%	41.18%	60.00%	0.5215

Table 2. Effect of the previous band-pass filtering on the classification between groups N and T using $H(2)$.

	Se	Sp	Acc	AROC
Original	57.69%	82.35%	71.67%	0.6640
3–9 Hz	97.06%	84.62%	91.67%	0.9559
MAW	91.18%	100.00%	95.00%	0.9796

recording was calculated. The performance of $H(2)$ over the original and filtered signals is presented in Table 2 and Figure 1. The use of a previous band-pass filtering improved the classification results with respect to the direct application of $H(2)$ to the signals. Moreover, the best results were obtained computing $H(2)$ on the MAW, as shown in Table 2.

Finally, $H(2)$ was computed on all non-overlapping 15 seconds segments of the MAW and the average value for each recording was obtained. Table 3 presents the classification results obtained from the analysis of the last 60, 45, 30 and 15 seconds of each recording. An accuracy value of 95% was attained in all cases. However, the highest value of AROC corresponds to the analysis of the last 15 seconds of each recording. As a consequence, this segment from the recording was selected as the optimal in this study.

5. Discussion

In the present work the optimal use of $H(2)$ in the estimation of AF organization has been determined. The use of a previous band-pass filtering allows to avoid the effect of noise and ventricular residua in the performance of non-linear metrics applied to the study of AF signals [17]. In this work it has been demonstrated that the application of a band-pass filtering stage, with a bandwith of 3Hz, to the atrial activity signal is recommended to obtain a high accuracy in the discrimination between AF signals with different organization levels. This recommendation in the use of $H(2)$ is consistent with the results presented in previous works [5, 17]. Furthermore, the use of the MAW achieved better classification results than a band-pass filtering in the typical AF frequency band, which would preserve more information. This may be because the dominant atrial frequency and the nearby frequencies contain most of the essential information from the atrial activity.

Additionally, the results presented in this work show that $H(2)$ can be applied optimally to very short segments of ECG recordings with good accuracy. As a consequence, its range of applicability can be extended not only to Holter recordings, but also to ambulatory AF recordings.

Table 3. Classification results of $H(2)$ computed over the MAW analyzing the last seconds of each recording.

	Se	Sp	Acc	AROC
60 s	91.18%	100.00%	95.00%	0.9796
45 s	91.18%	100.00%	95.00%	0.9796
30 s	91.18%	100.00%	95.00%	0.9796
15 s	91.18%	100.00%	95.00%	0.9830

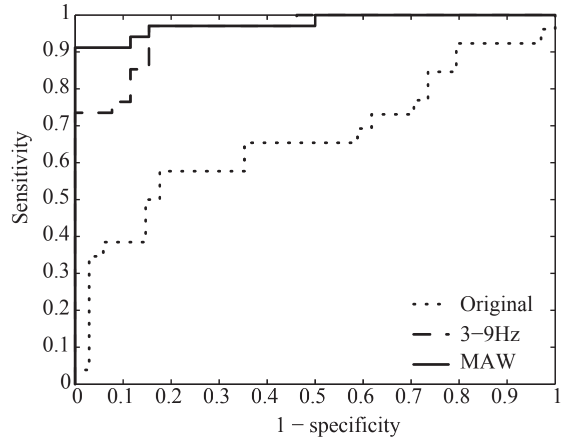

Figure 1. ROC curves obtained computing $H(2)$ on the original and filtered signals.

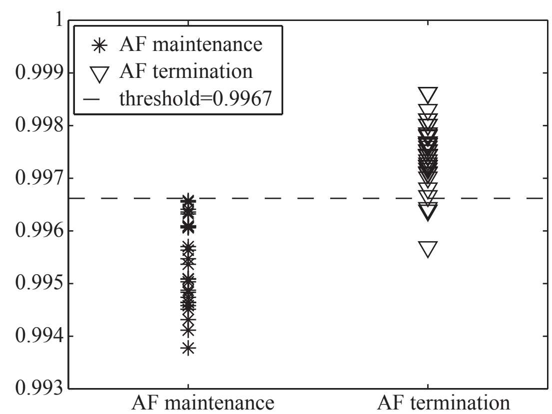

Figure 2. Optimal classification between groups N and T using $H(2)$

6. Conclusions

The present work has demonstrated that the generalized Hurst exponents are able to discriminate between AF signals with different organization levels. As a consequence, it can be proposed as a new alternative to non-invasive organization estimation in AF. Furthermore, the use of the Main Atrial Wave improves the performance of $H(q)$ in the organization estimation. Finally, this metric has yielded optimal classification results on short segments of few seconds. As a consequence, it could be applied to the analysis of ambulatory ECG recordings.

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