Non-Linear Analysis of the Main Atrial Wave to Estimate Organization in Paroxysmal Atrial Fibrillation

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Abstract

The analysis of spontaneous Atrial Fibrillation (paroxysmal AF) termination or maintenance could avoid unnecessary therapy and contribute to take the appropriate decisions on its management. The aim of this work is to study if an AF episode terminates spontaneously or not by analyzing the increase of atrial activity (AA) organization prior to AF termination. The organization varies as a consequence of the decrease in the number of reentries into the atrial tissue. The analysis was carried out noninvasively through the use of surface electrocardiogram (ECG) recordings. Sample entropy (SampEn) was selected as non-linear organization index. It was observed that noise and ventricular residues degrade AA organization estimation performance, therefore the use of selective filtering to get the main atrial wave (MAW) was necessary. Using the MAW organization analysis, that is the signal produced by the fundamental atrial waveform, 46 out of 50 of the terminating and non-terminating analyzed AF episodes were correctly classified (92%). Therefore, this method can provide a clear benefit for patients, doctors and health systems, since it avoids useless therapeutic intervention and minimises the risks for the patients.

1. Introduction

Atrial Fibrillation (AF) is a supraventricular arrhythmia characterized by uncoordinated atrial activation. AF occurs when the electrical impulses in the atria degenerate into a rapid chaotic pattern [1]. On the ECG, AF is described by the replacement of P waves by fibrillatory waves (f waves) that vary in size, shape, and timing, associated with an irregular ventricular response. Consequently, when AF occurs, a notably disorganized atrial activity (AA) can be observed [2].

Clinically speaking, AF is the most common cardiac arrhythmia, affecting 1% of the general population. Considering its prevalence with age, this arrhythmia affects up to 15% of the population older than 80 and has an incidence that doubles with each advancing decade. Paroxysmal (spontaneously terminated) AF is, by evidence, antecedent to persistent AF, which requires a pharmacological or external electrical intervention (cardioversion) to allow its termination [1]. AF predisposes to thrombus formation within the atria that can cause stroke or any other thromboembolic events [3]. Thus, the prediction of AF termination, based on non-invasive techniques, can be of great clinical value in order to avoid useless therapeutic interventions and to minimice the associated risks.

The most widely accepted theory to explain AF is based on the continuous propagation of multiple wavelets (called reentries) wandering throughout the atria [1]. The number of simultaneous reentries depends on the refractory period, mass and conduction velocity along the atria. On the other hand, several studies have demonstrated a decrease in the number of reentries prior to AF termination, thus producing simpler wavefronts and f waves evolve to P waves. In other words, the AA slightly evolves to a more organized pattern before AF termination [2]. This fact can be used to predict AF termination when the proper organization analysis tools are used.

Previous groups studied non-linear complexity indexes to characterize AA organization from the surface ECG, but their results did not revealed significative differences between terminating and non-termating AF episodes. The low signal to noise ratio was considered as the main reason to this unsuccessful result [4]. Therefore, a reduction of noise, ventricular residues, and any other nuisance signal could give positive results with non-linear analysis.

In the present work, the AA obtained from the surface ECG has been processed making use of selective filtering adapted to the peak atrial frequency. Next, the main atrial wave (MAW) was obtained. The MAW can be considered as the signal associated to the fundamental atrial waveform, its wavelength being the inverse of the AA main frequency [5]. The MAW organization has been estimated by means of sample entropy (SampEn), to discriminate between terminating and non-terminating AF episodes. This non-linear tool quantifies the regularity of a time series [6]

and its use in this study is justified because (i) the non-linearity, as necessary condition for a chaotic behavior, is present in the diseased heart with AF at cellular level and (ii) the electrical remodelling in AF is a far-from-linear process [7].

2. Materials

2.1. Database

The used database contained 50 one minute and two leads (II and V1) electrocardiogram (ECG) recordings, which were available in Physionet [8]. They were extracted from 24-hour Holter recordings from 50 different patients. The database included non-terminating AF episodes (group N), which were observed to continue in AF for at least one hour following the end of the excerpt, and AF episodes terminating immediately after the end of the extracted segment (group T). Recordings were divided into a learning and a test set. Next, 10 labelled recordings of each group formed the learning set. An optimal threshold, which should allow to discern between terminating and non-terminating paroxysmal AF episodes, was defined making use of the proposed methodology together with the learning set. Finally, the test set was composed with the remaining 30 recordings.

2.2. Data preprocessing

The ECG recordings were preprocessed in order to reduce noise, nuisance interferences and improve later analysis. Firstly, baseline wander was removed making use of bidirectional high pass filtering with 0.5 Hz cutt-off frequency [9]. Secondly, high frequency noise was reduced with a eight order bidirectional IIR Chebyshev low pass filtering, whose cut-off frequency was 70 Hz [10]. Finally, powerline interference was removed through adaptive filtering, which preserves the ECG spectral information [11].

3. Methods

3.1. Sample entropy

Sample Entropy (SampEn) examines time series for similar epochs and assigns a non-negative number to the sequence, with larger values corresponding to more complexity or irregularity in the data [12]. Two input parameters, a run length m and a tolerance window r, must be specified for SampEn to be computed. $SampEn(m, r)$ is the negative logarithm of the conditional probability that two sequences similar during m points remain similar at the next point, where self-matches are not included in calculating the probability. Thus, a lower value of SampEn

also indicates more self-similarity in the time series. SampEn is largely independent on record length [6, 12]. A more detailed mathematical description can be found in [12].

Although m and r are critical in determining the outcome of SampEn, no guidelines exist for optimizing their values. Nevertheless, the m and r values suggested by Pincus are $m = 1$ or $m = 2$ and r between 0.1 and 0.25 times the standard deviation of the original time serie [13].

3.2. Main atrial wave derivation and classification

The proposed methodology to obtain the MAW is shown in Fig. 1. Firstly, cancellation of QRST waves from the ECG signals was performed, obtaining a raw approximation to the MAW. Though a variety of QRST cancellation techniques exist, the average QRST template cancellation method was used, since only two leads were available [14]. Next, the power spectral density (PSD) of the residual signal was calculated using Welch Periodogram. A Hamming window of 4096 points in length, a 50% overlapping between adjacent windowed sections and a 8192-points Fast Fourier Transform (FFT) were used as computational parameters. The frequency with the largest amplitude within the 3-9 Hz range was selected as the dominant atrial frequency. Finally, the MAW was obtained applying a selective filtering to the AA signal centered around the dominant atrial frequency.

To prevent distortion, a linear phase FIR filter was used [15]. Chebyshev approximation was preferred because all the filter parameters can be suitably fitted and minimum ripple in the pass and stop bands were needed. Therefore, a high order filter should be used, such as the Kaiser approximation marks [16]:

$$M = \frac{-20 \log_{10}(\sqrt{\delta_1 \delta_2}) - 13}{14.6 \Delta f} + 1 \qquad (1)$$

where M is the filter order, δ_1 and δ_2 are the pass and stop bands ripple, respectively, and Δf is the transition bandwidth between bands. A selective filter must have δ_1 and δ_2 lower than 0.5% of the gain and Δf lower than 0.01 Hz, thereby its order must be greater than 250.

The selected filter bandwidth should be lower than 6 Hz because the typical frequency range of the AA is around 3-9 Hz [17]. In our experiments, the best results were obtained with a 3 Hz bandwidth and 768 filter coefficients. The MAW organization results obtained through the application of SampEn to the learning set, defined empirically the optimum threshold (Th) that, later, will allow the test set classification into terminating and non-terminating AF episodes.
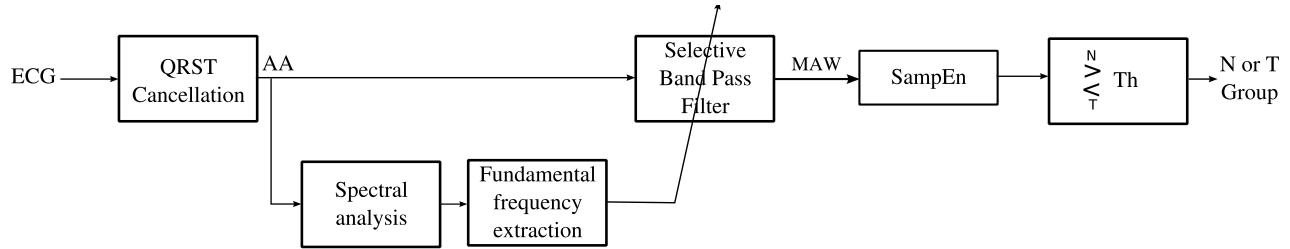
Figure 1. Block diagram describing the proposed methodology. Firstly, the ventricular activity is removed from the input ECG to obtain the AA. Next, a low bandwidth selective filter is applied to the atrial signal. The filter is centered around the dominant atrial frequency. SampEn is computed on the resulting signal and threshold compared in order to decide if the episode terminates.

4. Results

The proposed methodology was applied to the learning set and 100% sensivity and 90% specificity were obtained, see Fig. 2(a). The Receiver Operating Characteristic (ROC) curve provided 0.084115 as optimum SampEn discrimination threshold between terminating and non-terminating AF sets.

Fig. 2(b) shows the SampEn values for the 20 learning signals together with the mean and standard deviation values for each group. Note that all non-terminating and 9 out of 10 terminating recordings (95% of the learning signals) can be correctly discriminated.

Making use of the aforementioned SamEn threshold, 27 out of 30 test signals (90%) were correctly classified, see Fig. 2(c). Therefore, the AF behaviour of 46 out of 50 recordings (92%) were correctly predicted through the MAW organization analysis.

The SampEn mean value and standard deviation for all terminating and non-terminating AF recordings, and the statistic significance obtained by the t-student are shown in Table 1. Note that the terminating episodes present lower SampEn values than the non-terminating ones. Indeed, both paroxysmal AF groups are statistically distinguishable, given that statistic significance is notably lower than 0.01. Finally, remark that the obtained SampEn values are quite low, because of the MAW is a notably regular wave.

Table 1. Mean value and standard deviation for T and N sets and the t-student statistical significance.

	N Group	T Group
Mean $\pm$ Std	0.1047 ± 0.01352	0.0747 ± 0.0156
p	0.00000000245	

5. Discussion and conclusions

By analyzing with SampEn main atrial wave organization prior to spontaneous AF termination, 92% of the ter-

minating and non-terminating AF episodes were correctly classified. In order to obtain the MAW, the AA signal was firstly extracted. Several ways to extract the AA from surface ECG recordings have been presented. The latest presented methods take advantage of multiple lead information by solving the blind source separation problem [18]. Other methods are based on ventricular activity cancellation, such as QRST template matching and subtraction [14] or spatiotemporal QRST cancellation [17]. These methods obtain the (so called) remainder ECG that consists mainly of the AA. In this study, the QRST cancellation method was used [14].

Bearing in mind that the mean or median beat cannot represent each individual beat accurately, since QRST morphology is affected by respiration, patient movement, etc., QRST residuals and noise are often present in the remainder ECG [19]. These nuisance signals degrade AA organization estimation provoking very poor results when direct AA organization analysis was applied [4] and, consequently, MAW obtention was necessary.

This method can provide a clear benefit for patients, doctors and health systems, since it avoids useless therapeutic intervention (cardioversion) and minimises the risks for the patients. However, off-line analysis and high computational burden are limitations that should be refined.

Acknowledgements

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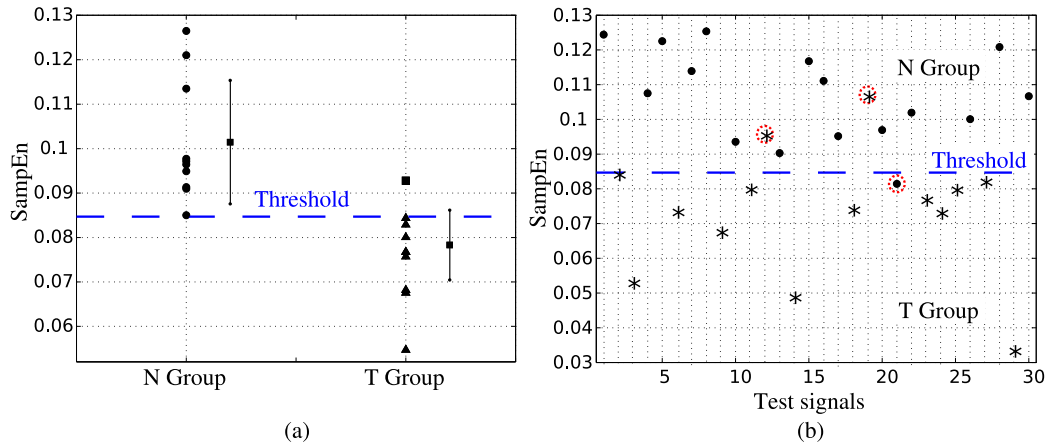
Figure 2. Classification into non-terminating and terminating AF for the recordings in (a) learning set and (b) test set.

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