Wavelet Sample Entropy: A New Approach to Predict Termination of Atrial Fibrillation

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Abstract

The mechanisms that provoke the eventual termination of some self paroxysmal fibrillation (PAF) episodes still remain unexplained. The aim of this to discriminate between between the groups of terminating (T registers) and non-terminating (N registers) of PAF episodes by using the ECG. A new technique, called Wavelet Sample Entropy (WSE) is proposed. WSE exploits the combination of wavelet transform properties with regularity measure indexes, as Sample Entropy (SampEn).

Results indicae that terminating episodes present lower mean values of SampEn than the non-terminating episodes. These results are consistent with the fact that fibrillatory activity become slower and more organized prior to termination. Both PAF groups were statistically distinguishable, given that the statistic significance obtained by the t-student test equals to 0.001 and 90% of test signals are correctly classified.

This new method could improve the efficiency of traditional discrimination techniques, based on time or frequency analysis, and it could be helpful for a better understanding of atrial fibrillation mechanisms.

1. Introduction

Atrial fibrillation (AF) is the most common arrhythmia encountered in clinical practice with a prevalence of 0.4% of the general population and over 6% of people over 80 years old [1]. Nowadays, the physiological mechanisms that provoke the eventual termination of AF episodes are still unexplained [2].

AF can be subdivided into different forms, namely 1) paroxysmal AF, i.e., self-terminating AF within 7 days, 2) persistent AF in which interventions are required for its termination, and 3) permanent AF in which sinus rhythm cannot be restored or maintained. About 18% of paroxysmal AF degenerate into permanent AF in 4 years [2]. Therefore, the study of paroxysmal AF is important for several reasons. Firstly, identification of onset and termination mechanisms may lead to better pathophysiological understanding of the arrhythmia and, accordingly, more effective therapy. Secondly, the prediction of spontaneous AF termination can avoid unnecessary therapy. In contrast, the prediction of AF maintenance can help in the use of appropriate interventions to prevent or manage AF chronification.

The aim of this work is to investigate the possibility to predict if and when AF episodes will terminate spontaneously, using surface electrocardiogram (ECG) signals, which are obtained by means of noninvasive techniques. In order to achieve this goal, a new technique called Wavelet Sample Entropy (WSE) is proposed. WSE tries to characterize the degree of organization of atrial activity (AA) during an AF episode. In this technique, firstly, the AA is obtained with a QRST cancellation technique. Secondly, the AA is decomposed by Wavelet Transformation (WT) in different detail and approximation coefficients. Finally, the Sample Entropy (SampEn) of some time-reconstructed selected coefficients is calculated, showing that there exist relevant differences between terminating and non terminating PAF episodes.

2. Database and methods

2.1. Datasets

PhysioNet provides free access to 50 one minute electrocardiogram recordings extracted from 24-hour holter recordings from 50 different patients, which are available through PhysioBank [3]. This database includes non-terminating AF (group N), which were observed to continue for at least one hour following the end of the excerpt, and AF terminating immediately after the end of the extracted segment (group T). Ten labeled recordings of each group were supplied as a learning set. The remaining 30 recordings were used as the test set.

In order to facilitate the study, an extraction of QRST complexes from ECG signals has been realized, obtaining an approximation of the AA signals. Many QRST cancellation techniques exist, but the mean QRST cancellation technique has been used, since only two leads were available. For QRS detection, the point of maximum negative slope is chosen as the fiducial point. An adaptive average beat is calculated and a template of time-sliding average beats is generated and subtracted from the original ECG signal [4, 5].

2.2. Methods

2.2.1. Wavelet transform principles

The contribution of the wavelet analysis to the non-invasive electrocardiography has increased in the last years. ECG compression [6], ECG pattern recognition [7], heart rate variability [8] and noise and interferences reduction [9] are some examples of this contribution.

To summarize, the Wavelet analysis transforms the signal under investigation into another one that includes both frequency and time domain information. The signal is decomposed in basic blocks, called detail and approximation coefficients, corresponding to different frequency bands. A detailed description of wavelet theory can be found in [10].

2.2.2. Entropy

Entropy provides a complexity measure of a time series, such as discretized biological signal [11]. Examples are approximate entropy (ApEn) [12] and its modification, sample entropy (SampEn) [13]. ApEn provides a measure of signal regularity i.e., the presence of similar patterns in the time series, and assigns a nonnegative number to a time series, with larger values corresponding to more complexity or irregularity in the data.

Formally, given N data points from a time series $\{x(n)\} = x(1), x(2), \ldots, x(N)$, the algorithm forms m-vectors $X(1), \ldots, X(N-m+1)$ defined by: $X(i) = [x(i), x(i+1), \ldots, x(i+m-1)], i = 1, \ldots, N-m+1$. For a given $X(i)$ count the number of j ($j = 1, \ldots, N-m+1$) so that $d[X(i), X(j)] \leq r$, denoted as $N^m(i)$, and being $d[X(i), X(j)] = \max_{k=1,2,\ldots,m} |x(i+k-1) - x(j+k-1)|$. Then, for $i = 1, \ldots, N-m+1$

$$C_r^m(i) = \frac{N^m(i)}{N-m+1} \tag{1}$$

$C_r^m(i)$ measures, within a tolerance r, the frequency of patterns similar to given one of window length m. ApEn is defined as

$$ApEn(m, r, N) = \phi^m(r) - \phi^{m+1}(r) \tag{2}$$

where

$$\phi^m(r) = \frac{1}{N-m+1} \sum_{i=1}^{N-m+1} \ln C_r^m(i) \tag{3}$$

In some cases, ApEn lacks of consistency. For example, its computation in irregular time series is affected by a bias, which may cause an overestimate of the entropy value, mostly when r values are very small. A modification of the ApEn algorithm is SampEn, which removes the deficiencies reported here. The differences with respect to ApEn are: 1) self-matches are not counted; 2) only the first $N-m$ vectors of length m are considered; and 3) the conditional probabilities are not estimated in a template manner. Thus, the probability measure is computed directly as the logarithm of conditional probability instead of the ratio of the logarithmic sums [13].

2.2.3. Wavelet Sample Entropy

In order to reduce the noise and to improve the signal-to-nose ratio in the AA signal [14], a seven levels wavelet decomposition was applied to the data, using ”bior6.8” as wavelet family. As the fundamental frequency of AA signal is included between 4 and 10 Hz [4], the frequency sub-band of interest corresponds to detail coefficients 5, 6 or 7 (sampling frequency is 1000 Hz).

The whole process applied to each ECG recording is the following. Firstly, the AA is obtained with a QRST cancellation technique. Secondly, this AA is decomposed using WT in different detail and approximation coefficients. The power spectrum of AA is calculated using the Fast Fourier Transform (FFT) and its fundamental frequency is extracted. The frequency band containing that fundamental frequency is reconstructed back to the time-domain. SampEn of this time reconstructed signal is calculated, showing relevant differences between both PAF groups. The complete process is shown in Fig. 1.

In this study SampEn was estimated using the widely established parameter values of $m = 2$, and $r = 0.25\sigma$, being σ the standard deviation of the original data sequence, as suggested by Pincus [12].

A similar methodology has been used in the analysis of electroencephalograms (ECG) in previous studies, obtaining a successful results [14, 15, 16]. However, this work shows the first satisfactory results over the nonlinear analysis of AF using surface ECG [17].

3. Results

3.1. Learning set

Applying WSE to the CinC/Physionet Challenge 2004 proposed training set, a 90% sensitivity and a 90% specificity were obtained, see Fig. 2. The ROC curve allows to fix the optimum threshold of SampEn (Th=0.09165) to discriminate between the groups of terminating and non-terminating PAF episodes.

Fig. 3 shows the SampEn values for the 20 learning signals, and the mean and standard deviation values for each group. It can be observed that 9 out of 10 signals

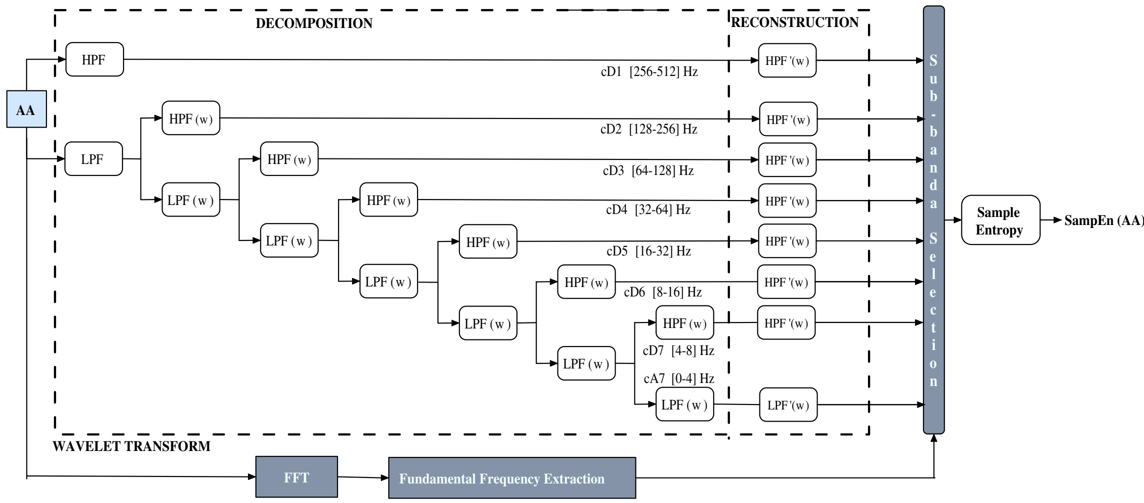

Figure 1. Wavelet Sample Entropy.

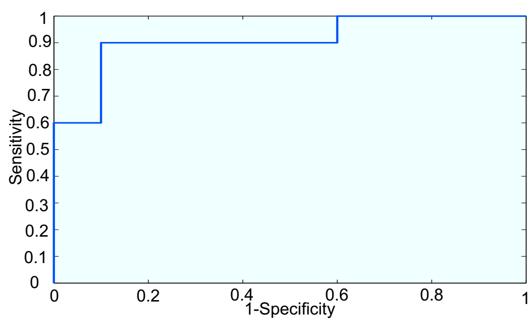

Figure 2. Receiver Operating Characteristic Curve.

from each group can be discriminated. In addition, the terminating episodes present lower mean values of SampEn (0.0868±0.0062) than the non-terminating episodes (0.0975±0.0051). Indeed, both PAF groups are statistically distinguishable, given that the statistic significance obtained by the t-student test equals to 0.001. Moreover, these results agree with the fact that fibrillatory activity slows and organizes prior to termination, as it has been reported in previous works [4, 18].

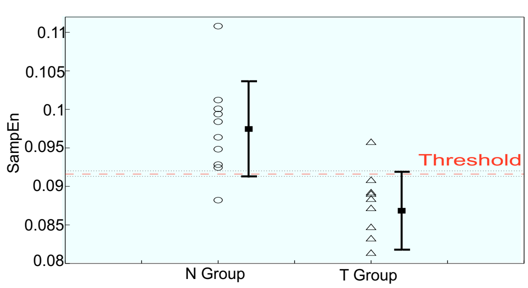

Figure 3. WSE applied learning signals.

3.2. Test set

With WSE and the threshold obtained with the training signals, 27 out of 30 test signals were correctly classified, see Fig. 4. These results corroborate the conclusions obtained with the learning set of signals. However, it can be observed that SampEn values are very low, because of the AA signals are very regulars, see Fig. 5.

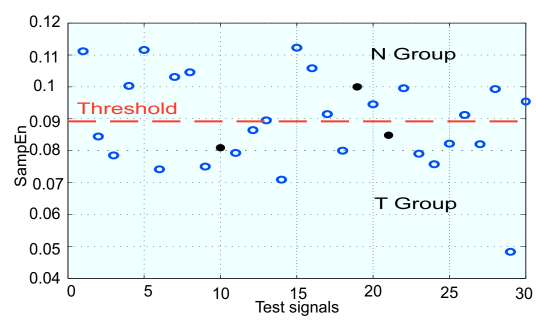

Figure 4. WSE applied test signals. The black marks are the signals non-correct identified.

These results are similar to the presented skills in Challenge 2004 [19], therefore a combination of WSE and the frequency-based methodology may provide a more robust and reliable method to discriminate between T and N group of signals.

4. Conclusions

In this work a novel technique, WSE, that predicts the termination of PAF episodes, has been presented. WSE is based on the measurement of atrial activity regularity, which is obtained by means of non-linear methods, as sample entropy. In addition, wavelet transform allows to isolate certain time frequency characteristics in limited decomposition coefficients which permits to see changes in the regularity of the AA signal, that would be left masked in other cases. Moreover, WT is able to increase the SNR in AA signal, thus more satisfactory results than in other studies are obtained. Results show that this new method could improve the efficiency of classical techniques of discrimination based on frequency analysis and could help to gain some additional knowledge in atrial fibrillation mechanisms.

An important conclusion derived from this study is that it is possible to determine if AF will terminate with good accuracy (90%). The prediction of AF termination is based on the analysis of the AA signal, that confirms the initial hypothesis that any useful information about the mechanisms that cause AF should be extracted from atrial fibrillatory wave. Moreover, it is possible to extract information of important clinical use by means of noninvasive techniques, such as the ECG analysis, which may lead towards the development of improved therapeutic interventions for the treatment of AF.

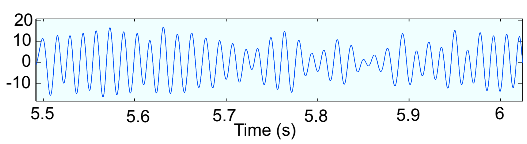

Figure 5. Time Wavelet reconstruction of selected band frequency.

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