WAVELET SAMPLE ENTROPY OPTIMIZATION THROUGH OPTIMAL MOTHER FUNCTION SELECTION FOR ATRIAL FIBRILLATION ANALYSIS

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Abstract: Wavelet Sample Entropy (WSE) has been previously introduced as a successful methodology to predict electrical cardioversion (ECV) outcome of persistent atrial fibrillation (AF). The method estimates AF organization based on the combination of Wavelet decomposition and non-linear regularity metrics, such as Sample Entropy (SampEn). However, WSE has been only computed by applying a specific wavelet function, such as the fourth-order biorthogonal wavelet. In the present work, with the objective of improving WSE robustness and its diagnostic ability in ECV outcome prediction, several orthogonal wavelet families were tested, and their performances were compared. Results indicated that, for all the functions of the same wavelet family, the same sensitivity and specificity were obtained. Additionally, all the wavelet families reached the same diagnostic ability (80.95% sensitivity and 85.71% specificity), being the same patients incorrectly classified by all the families. These results suggest that any wavelet family could be indistinctly used to estimate successfully AF organization with the WSE methodology. As a consequence, the design of a customized wavelet function adapted to the specific characteristics of AA would not improve the WSE diagnostic ability in the prediction of ECV outcome in AF.

1 INTRODUCTION

For patients in persistent atrial fibrillation (AF), restoration and maintenance of normal sinus rhythm (NSR) is the main therapeutic goal because symptoms, cardiac output, and exercise tolerance are improved whereas the risk of stroke is reduced (Fuster et al., 2006). Thus, the first step in the rhythm control strategy is generally cardioversion. While chemical-induced cardioversion is sometimes possible, particularly with amiodarone (Gall and Murgatroyd, 2007), it is generally more unsuccessful than electrical cardioversion (ECV), specially if the arrhythmia has been present for more than 24 hours (Gall and Murgatroyd, 2007). However, although the ECV success rate is high, AF recurrence is common, especially during the first 2 weeks following the procedure (Tieleman et al., 1998). Moreover, ECV also has the potential of causing severe collateral effects, such as post-shock bradycardia, malignant ventricular arrhythmias, arterial thromboembolism and complications related to anaesthesia (Gall and Murgatroyd, 2007). Hence, it would be clinically very useful to predict NSR maintenance after ECV, before it is attempted. In this way, the risks of cardioversion could be avoided for those patients with high risk of short-term recurrence and, for the health care provider, clinical costs could be reduced because unproductive treatment time and bed usage could be reduced.

Recently, a strategy defined as Wavelet Sample Entropy (WSE) has been introduced as a successful methodology to predict ECV outcome (Alcaraz and Rieta, 2008). The method estimates AF organization based on the combination of Wavelet decomposition and non-linear regularity metrics, such as Sample Entropy (SampEn), showing that in patients with a more organized AF, the arrhythmia recurrence likelihood was lower after ECV (Alcaraz and Rieta, 2008). However, WSE was only computed by applying a specific wavelet function, such as the fourth-order biorthogonal wavelet. Thereby, in the present work, with the objective of improving the robustness

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of WSE and its diagnostic ability in ECV outcome prediction, several orthogonal wavelet families were tested, and their performances were compared.

2 MATERIALS

2.1 Study Population

Thirty-five patients (12 men and 23 women) with persistent AF lasting more than 30 days, undergoing the first attempt of ECV were followed during four weeks. All patients were in drug treatment with amiodarone. A standard 12-lead ECG was acquired prior to cardioversion. All signals were digitized at a sampling rate of 1024 Hz and 16-bit resolution with a Cardiolab System in the electrophysiology laboratory during ECV protocol. In order to process these signals, a 30 seconds-length AF segment preceding the ECV was extracted for each patient. After the ECV, in 21 patients (60%) NSR duration was below one month, whereas en the remaining 14 patients (40%) NSR was maintained.

2.2 Data Preprocessing

Lead V_1 was chosen for the analysis because previous works have shown that atrial activity (AA) is dominant in this lead (Petrutiu et al., 2006). The signal was preprocessed in order to improve later analysis. Firstly, baseline wander was removed making use of bidirectional high pass filtering with 0.5 Hz cutt-off frequency (Dotsinsky and Stoyanov, 2004). Secondly, high frequency noise was reduced with an eight order bidirectional IIR Chebyshev low pass filtering, whose cut-off frequency was 70 Hz (Sun et al., 2002). Finally, powerline interference was removed through adaptive notch filtering, which preserves the ECG spectral information (Ferdjallah and Barr, 1994).

3 METHODS

3.1 Wavelet Sample Entropy

The WSE methodology has shown an ability to detect regularity variations in the AA signal that would be left masked in other cases (Alcaraz and Rieta, 2008). However, this strategy requires the combination of Wavelet decomposition and SampEn together with some additional previous steps, such as it will be next described.

The analysis of the AA from the surface ECG is complicated by the simultaneous presence of ventricular activity, which is of much greater amplitude. Whereby, the AA signal has to be firstly extracted before the application of any other analysis. Although a variety of different techniques exist for this purpose, a QRST cancellation method was used. Thus, the highest variance eigenvector of all the ECG beats was considered as the ventricular template for the cancellation. This QRST template was selected because it provided a more accurate ventricular activity representation and, hence, higher quality AA extraction in short AF recordings, such as the analyzed in this work, than those obtained by averaging all the beats (Alcaraz and Rieta, 2007).

Next, eight levels of wavelet decomposition were applied to the AA signals because the seventh detail scale (sub-band corresponding to $4-8$ Hz) covers the most typical AA frequency range (Bollmann et al., 2006). The wavelet coefficients vector corresponding to the scale containing the dominant atrial frequency, those with the largest amplitude within the AA frequency range (Bollmann et al., 2006), was linearly interpolated by the factor 2^{m-1}, being m the discrete wavelet scale. Hence, a vector of wavelet coefficients with a number of samples equal to the original signal was obtained for the chosen scale. Considering that different scales present wavelet coefficients vectors with different number of samples, this interpolation was necessary. Moreover, unsuccessful results were obtained when non-interpolated wavelet coefficients vectors were analyzed. Finally, the regularity of this vector was estimated making use of SampEn to discern between ECVs relapsing to AF and resulting in NSR.

3.2 Wavelet Family Selection

Given that there are no established rules for the choice of a specific wavelet family for each particular application, several orthogonal wavelet families were tested in this work. Only experiments with orthogonal families were developed because only in an orthogonal basis any signal can be uniquely decomposed and the decomposition can be inverted without loosing information (Mallat, 1999). Concretely, all the different functions from Haar, Daubechies, Coiflet, Biorthogonal, Reverse Biorthogonal and Symlet wavelet families were tested.

3.3 Statistical Analysis

The obtained SampEn values were expressed as mean $\pm$ standard deviation, because ECVs relapsing to AF

Table 1: Mean and standard deviation SampEn values for ECVs relaping to AF and resulting in NSR, statistical significance (*p* value), sensitivity and specificity for each tested wavelet family.

Wavelet family (order)	ECVs relapsing AF	ECVs maintaining NSR	*p*-value	Sensitivity (%)	Specificity (%)
Haar	0.030 ± 0.006	0.026 ± 0.005	0.0100	80.95 (17/21)	85.71 (12/14)
Daubechies (5)	0.031 ± 0.006	0.027 ± 0.006	0.0112	80.95 (17/21)	85.71 (12/14)
Coiflet (3)	0.030 ± 0.007	0.025 ± 0.006	0.0098	80.95 (17/21)	85.71 (12/14)
Biorthogonal (4.4)	0.032 ± 0.005	0.027 ± 0.004	0.0072	80.95 (17/21)	85.71 (12/14)
Reverse Biorthogonal (4.4)	0.033 ± 0.006	0.029 ± 0.004	0.0115	80.95 (17/21)	85.71 (12/14)
Symlets (5)	0.031 ± 0.006	0.026 ± 0.005	0.0086	80.95 (17/21)	85.71 (12/14)

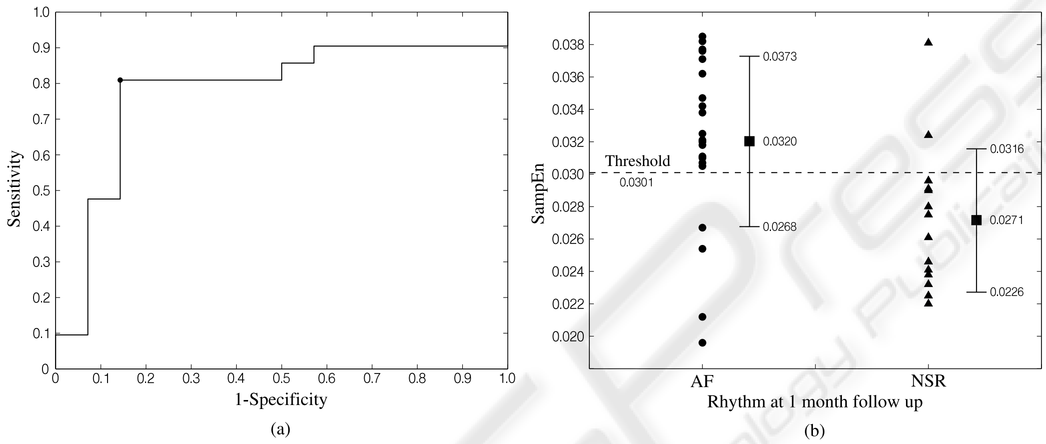

Figure 1: Results obtained with the third-order Coiflet wavelet family. (a) ROC curve constructed with the obtained SampEn values for persistent AF patients. The closest point to 100% sensitivity and specificity is selected as optimum SampEn threshold. Symbol • indicates the optimum threshold. (b) Classification into patients resulting in NSR and relapsing to AF after 4 weeks following ECV.

and resulting in NSR had a normal and homoscedastic distribution as the Kolmogorov–Smirnov and Levene tests proved, respectively. Thereby, The *t* Student test was also used to determine whether there was any significant difference between the groups. A two-tailed value of $p < 0.05$ was considered statistically significant.

In order to evaluate the predictive ability for the NSR maintenance reached through each wavelet function, receiver operating characteristic (ROC) curves were constructed. Different thresholds or cutoff points (SampEn values) were selected and the sensitivity/specificity pair for each one of them was calculated. Sensitivity (the true positive rate) was considered as the ECVs relapsing to AF proportion correctly classified (SampEn value higher than the cutoff point), whereas specificity (the true negative rate) represented the ECVs resulting in NSR percentage correctly recognized (SampEn value lower than the cutoff point). The closest point to 100% sensitivity and specificity was selected as optimum SampEn threshold.

4 RESULTS

For all the functions of the same wavelet family, the same sensitivity and specificity values were obtained. Thereby, only the function that showed lower *p* value is presented in Table 1 for each wavelet family.

As can be appreciated in the table, all the wavelet families reached the same efficiency, i.e. a sensitivity of 80.95% (17 out of 21) and a specificity of 85.71% (12 out of 14), being the same patients incorrectly classified by all the families. Additionally, for all the cases, the ROC curves provided an optimum SampEn discrimination threshold between 0.029 and 0.030. Similarly, for all the wavelet families, the patients relapsing to AF presented higher SampEn values than those resulting in NSR after one month, and both groups were statistically distinguishable, since a statistical significance lower than 0.001 was obtained. Fig. 1 shows the ROC curve and the classification into patients resulting in NSR and relapsing to AF obtained with the third-order Coiflet family as an example.

5 DISCUSSION AND CONCLUSIONS

The wavelet coefficients vector organization analysis checks the regularity of a time series. This time series is constituted by the correlation coefficients between the scaled mother wavelet and consecutive and non-overlapping signal segments. In this respect, results provided by all the tested wavelet families can be considered as coherent and prove that the discrete Wavelet transform translation variance has no effect in this application. Additionally, a high regularity value in this time series indicates constant waveform across the studied time period. On the contrary, low regularity implies variable waveforms. Thus, the presence of more structured f waves in organized atrial activities (Petrutiu et al., 2006) could justify the obtained results, which show that patients who relapsed to AF presented lower wavelet coefficients vector regularity than those who remained in NSR.

Hence, the obtained results suggest that the design of a customized wavelet function adapted to the atrial activity waveform characteristics would not considerably improve prediction of ECV result. In fact, in other studies, where different ECG problems were solved making use of WT, a new wavelet function adapted to the analyzed signal characteristics was considered but, finally, discarded (Addison, 2005).

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