Role of Fibrillatory Waves Amplitude as Predictors of Immediate Arrhythmia Termination After Maze Surgery of Atrial Fibrillation

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Abstract

Cox-Maze surgery is an effective procedure to terminate atrial fibrillation (AF) in patients requiring open-heart surgery associated to another heart disease. After the intervention, AF spontaneous reversion occurs immediately in some patients, but not in others. This work analyzes 23 twelve-lead preoperative ECGs from patients in AF to predict immediate termination of the arrythmia. To carry out the prediction, three indices have been studied: the dominant atrial frequency (DAF), the sample entropy (SampEn) and the fibrillatory waves average power (fWP). Results for the DAF yielded a Sensitivity (Se), Specificity (Sp) and Accuracy (Acc) of 78%, 71% and 74%, respectively. For SampEn 78%, 79% and 78%, respectively and for fWP were 89%, 71% and 78%, respectively. Finally, to improve the prognosis capability a classification tree combining the analyzed parameters was created yielding Se, Sp and Acc of 89%, 93% and 91%, respectively. As conclusion, the combination of fWP with DAF and SampEn has provided very auspicious results to predict whether AF would terminate immediately after the Cox-Maze surgery.

1. Introduction

The Cox-Maze procedure is a surgical treatment for AF introduced by Dr Cox [1]. After two iterations, due to several postoperative drawbacks, Cox-Maze III procedure was introduced and has remained the gold standard for surgical treatment of AF [2]. Cox-Maze III procedure is an open-heart intervention assuming that AF results from multiple macro-reentry circuits in the atria [2]. Thus, the procedure consists of forming scar tissue in the atria by means of surgical incisions to block atrial conduction and interrupt the most commons macro-reentrant circuits [1].

After Cox-Maze procedure, reversion to normal sinus rhythm occurs in some patients, but, in others, it may take some days. For these latter cases, when AF still remains for a month, electrical cardioversion (ECV) is required [3]. Therefore, predicting the surgery outcome would be useful for clinicians to plan in advance antiarrhythmic treatment or ECV-related decisions. Thus, this work focuses on defining a robust method able to predict before surgery immediate reversion of AF after the Cox-Maze procedure.

Given that previous works proved that fibrillatory (f) waves amplitude was an accurate predictor of Cox-Maze surgery long term outcome [4], this work takes this index as a predictor of immediate AF termination after Cox-Maze. This parameter is studied by computing f waves mean power (fWP), which has demonstrated to be an accurate indicator of f waves amplitude in previous studies [5].

In addition, atrial activity (AA) organization has been analyzed because previous studies have related AA organization to the number of propagating wavefronts throughout the atria. Hence, organization would indicate the likelihood of restoring normal sinus rhythm NSR [6]. Moreover, studies using surface ECGs have shown to be capable of studying AA organization to predict AF termination [7]. Therefore, the present work studies organization of the AA considering its relation to immediate AF termination after Cox-Maze surgery. To assess organization, two parameters are used: the dominant atrial frequency (DAF) [8] and sample entropy (SampEn) [7]. Finally, all the parameters will be combined through a classification tree to enhance prediction capability.

2. Materials

The database was composed of 20 seconds length segments from preoperative standard 12-lead ECGs recorded from 23 patients (mean age 68 $\pm$ 7 years). All the patients were in persistent AF and underwent surgery to valve surgical replacement. Data were recorded with a sampling frequency of 1kHz and with amplitude resolution of 0.4 μV. Immediately after the Cox-Maze surgery, 14 patients were still in AF (61%) while in 9 patients (39%) NSR was restored. As the Cox-Maze surgery is dependent of the surgeon skill, the same doctor practiced all Cox-Maze procedures to avoid surgeon-dependent bias.

For the analysis, lead V_1 was chosen because previous works have shown that the AA is prevalent in this lead [9]. The signals were processed with an adaptive notch filter in 50 Hz to remove the powerline interference. Then, high frequency noise was reduced with an eight-order forward/backward IIR Chebyshev lowpass filtering, whose cut-off frequency was 70 Hz. Next baseline wander was removed by bidirectional high-pass filtering with 0.5 Hz cut-off frequency. Finally, wavelet denoising was applied to reduce muscle noise [10]. After denoising, an adaptive QRST cancelation method was applied to the recordings in order to extract the AA [11].

3. Methods

3.1. Dominant atrial frequency

The DAF is an index from the frequency domain directly related to the atrial cycle length [8]. Several studies demonstrate that the AA signal spectrum has one or more components in the band of 3-9 Hz [8]. Therefore, the DAF is defined as the frequency with the highest amplitude within the 3-9 Hz range in the AA spectrum. To obtain the DAF, the Power Spectral Density (PSD) must be computed. In this work, the PSD was obtained using the Welch method with a Hamming window of 4096 points in length, 50% overlapping between adjacent windowed sections and a 8192-points fast Fourier transform (FFT) [12].

3.2. Sample entropy

SampEn examines time series for similar epochs and assigns a non-negative number to the sequence, with larger values corresponding to more irregularity in the data [13]. It is defined as the negative natural logarithm of the conditional probability that two sequences similar for m points remain similar at the next point, where self-matches are not included in calculating the probability [13]. Two input parameters must be specified to compute the SampEn, the length of the sequences to be compared, m, and the pattern similarity tolerance, r. As suggested in previous works, optimal values for AF analysis are $m = 2$ and $r = 0.35$ times the standard deviation of the AA [14].

SampEn is sensitive to noise and ventricular residua [15]. Therefore, it was computed over the main atrial wave (MAW) to reduce the influence of these nuisance signals [15]. The MAW was extracted by selective filtering the AA signal centered on the DAF. As in previous works, a linear phase Chebyshev FIR filter was applied with a 3 Hz bandwidth and 768 coefficients [15].

3.3. Atrial activity mean power

The fWP represents the energy carried by the f waves within the interval under analysis. Thus, it can be considered as a robust indicator of the AA signal amplitude [5]. The fWP is obtained by computing the root mean square value of the AA [5]. Before extracting the AA signal, each analyzed ECG segment was normalized to its maximum R peak amplitude. This operation avoided all the effects than can modify the ECG amplitude as a function of the different gain factors during recording, electrodes impedance, skin conductivity, etc [5]. This intra-patient normalization did not affect DAF computation, because the spectral distribution of a signal is independent of its amplitude, nor SampEn, because the tolerance r was normalized to the data standard deviation.

3.4. Statistical analysis

As SampEn is a non-linear time series metric, data nonlinearity was tested firstly. For testing nonlinearity, the procedure selected was the surrogate data tests. In this method, a set of surrogate data is obtained from the original dataset. Then, a number that quantifies some aspect of the series, called discriminating statistic, is computed. When the original series discriminating statistic is significantly different than the surrogate data values, non-linearity can be assumed [16]. Mutual information has been used as discriminating statistic in the present work [16] and non-linear behavior of AF has been verified.

Regarding prediction results, a study to determine statistical significance was performed. Firstly, a Shapiro-Wilk test was applied to analyze data distributions. As a result, only DAF and SampEn had a normal distribution, while the fWP was not normal.

t-Student test was applied to parameters with normal distribution, considering as statistically significant a two-tailed value of $p < 0.05$. The results shown that predictions obtained with SampEn were statistically significant, while predictions obtained using the DAF did not. On the other hand, the Mann-Whitney U test demonstrated that predictions with the fWP were statistically significant.

Finally, a threshold was defined for each predictor to classify in AF reversion or AF maintenance. The threshold for each index was obtained by computing their receiver operating characteristic (ROC) curve, which is a graphical representation of the tradeoffs between sensitivity and specificity. The thresholds selected were those that maximized the area under the curve together with sensitivity (Se) and specificity (Sp) of the corresponding feature.

Table 1. Results for DAF, SampEn, fWP and classification tree to discriminate into AF reversion or AF maintenance before Cox-Maze surgery. AF reversion has been considered the positive case.

	Se	Sp	Acc
DAF	78%	71%	74%
SampEn	78%	79%	78%
fWP	89%	71%	78%
Classification tree	89%	93%	91%

4. Results

To evaluate the parameters outcome, Se, Sp, and accuracy (Acc) were calculated. The results obtained are shown in Table 1, where the classification tree outcome is also shown. As can be noticed, the parameters related to organization present the same Se, which is lower than the associated to fWP. On the other hand, the best Sp is yielded by SampEn. Regarding accuracy, SampEn and fWP present same Acc while DAF shows lower Acc. Finally, the classification tree improves Se, Sp and Acc compared to the individual indices.

To analyze classification performance, the values obtained were graphically represented. The vertical axis was associated to the index value whereas the horizontal axis was divided into AF reversion or AF maintenance. DAF, SampEn and fWP classification results are shown in Figures 1, 2 and 3, respectively.

5. Discussion

The present work has introduced some parameters related to the f waves amplitude and organization to predict immediate AF termination after Cox-Maze surgery. This prediction is useful because facilitates better treatment planning and helps in preoperative and postoperative decisions. Despite the importance of an early prognosis, previous studies have focused on predicting long-term outcome since an immediate prediction is challenging due to the considerable changes occurring on the atrial tissue. The parameters studied have been DAF, SampEn and fWP.

Previous studies demonstrated that SampEn and DAF are highly correlated [17] but SampEn classifies better and the results obtained in this work agree with those studies. Regarding AF maintenance, DAF and SampEn performs an identical classification while regarding AF reversion, classification performed by both parameters is similar but better with the SampEn.

The f waves amplitude has been used in previous works to predict the NSR restoration after Cox-Maze procedure with a different method. The method consists of measuring

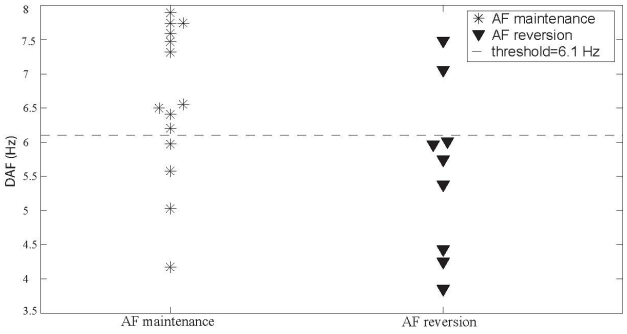

Figure 1. DAF values obtained from the atrial activity signals. Values above the threshold are supposed to be associated with AF maintenance while values below the threshold are supposed to be associated with AF reversion.

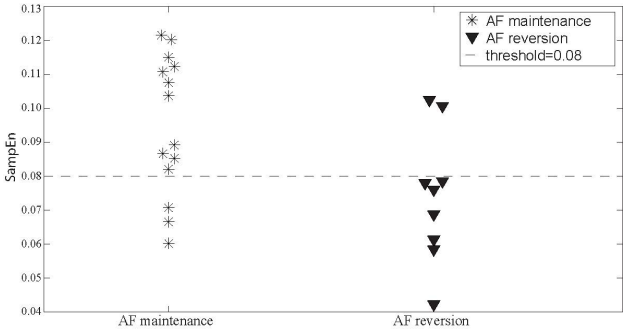

Figure 2. SampEn classification results. SampEn is higher when it is associated with AF maintenance, thus, values over the threshold are associated with AF maintenance.

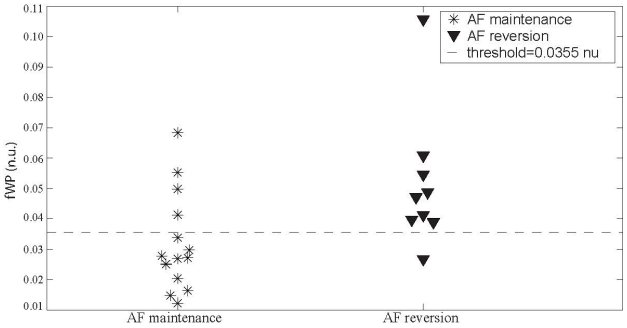

Figure 3. fWP classification results. Lower fWP values are associated with lower probability of AF reversion. Thus, values below this graphic threshold are associated with AF maintenance.

the greatest fibrillatory wave, with the aid of calipers, from the upper edge of the trough to the upper edge of the peak, and express it in millimeters [4]. This procedure is inaccurate and user-dependent, thus, this paper has proposed to study the f waves amplitude using the fWP, which is an automatic reliable method [5].

Finally, to improve the prediction capability, a classification tree was used combining the three parameters studied in this work. The classification tree achieved 89%, 93% and 91% for Se, Sp and Acc respectively.

The study performed showed auspicious results but there are some limitations that must be considered. The first limitation of the study is the relative low number of patients, and, therefore, the presented results must be considered with caution. Second, to avoid surgeon-dependent bias, the same doctor practiced all the maze procedures, thus, it is possible that a study performed with maze procedures performed by other surgeon presents slightly different results. Finally, the energy source used in the maze procedures was cryoablation and radiofrequency but there are other energy sources to carry out a maze procedure that could affect the results obtained.

6. Conclusions

Predicting spontaneous immediate AF termination after Cox-Maze surgery from preoperative ECGs is challenging due to the considerable transformation occurring on the atrial substrate. Moreover, the surgeon skill is a key aspect directly related with results. Due to those drawbacks there are few studies about immediate AF termination after Cox-Maze procedure. In this work, combination of the parameters fWP, SampEn and DAF has provided very auspicious results, suggesting that an accurate prediction is possible. Therefore, more studies are needed to validate the robustness of this prediction and the repeatability of the obtained results on wider databases.

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References

[1] Ad N. The Cox-Maze procedure: history, results, and predictors for failure. J Interv Card Electrophysiol Dec 2007; 20(3):65–71.

[2] Prasad SM, Maniar HS, Camillo CJ, Schuessler RB, Boineau JP, Sundt TM, Cox JL, Damiano RJ. The cox maze III procedure for atrial fibrillation: long-term efficacy in patients undergoing lone versus concomitant procedures. J Thorac Cardiovasc Surg Dec 2003;126(6):1822–1828.

[3] Ad N, Barnett S, Lefrak EA, Korach A, Pollak A, Gilon D, Elami A. Impact of follow-up on the success rate of the cryosurgical maze procedure in patients with rheumatic heart disease and enlarged atria. J Thorac Cardiovasc Surg May 2006;131(5):1073–1079.

[4] Kamata J, Kawazoe K, Izumoto H, Kitahara H, Shiina Y, Sato Y, Nakai K, Ohkubo T, Tsuji I, Hiramori K. Predictors of sinus rhythm restoration after Cox maze procedure concomitant with other cardiac operations. Ann Thorac Surg Aug 1997;64(2):394–398.

[5] Alcaraz R, Rieta JJ. The application of nonlinear metrics to assess organization differences in short recordings of paroxysmal and persistent atrial fibrillation. Physiol Meas Jan 2010;31(1):115–130.

[6] Sih HJ, Zipes DP, Berbari EJ, Olgin JE. A high-temporal resolution algorithm for quantifying organization during atrial fibrillation. IEEE Trans Biomed Eng Apr 1999; 46(4):440–450.

[7] Alcaraz R, Rieta JJ. A non-invasive method to predict electrical cardioversion outcome of persistent atrial fibrillation. Med Biol Eng Comput Jul 2008;46(7):625–635.

[8] Holm M, Pehrson S, Ingemansson M, Sörnmo L, Johansson R, Sandhall L, et al. Non-invasive assessment of the atrial cycle length during atrial fibrillation in man: introducing, validating and illustrating a new ECG method. Cardiovasc Res Apr 1998;38(1):69–81.

[9] Petrutiu S, Ng J, Nijm GM, Al-Angari H, Swiryn S, Sahakian AV. Atrial fibrillation and waveform characterization. A time domain perspective in the surface ECG. IEEE Eng Med Biol Mag 2006;25(6):24–30.

[10] Sörnmo L, Laguna P. Bioelectrical Signal Processing in Cardiac and Neurological Applications. Elsevier Academic Press, 2005. ISBN 0-12-437552-9.

[11] Alcaraz R, Rieta JJ. Adaptive singular value cancelation of ventricular activity in single-lead atrial fibrillation electrocardiograms. Physiol Meas Dec 2008;29(12):1351–1369.

[12] Welch PD. Use of Fast Fourier Transform for estimation of power spectra: A method based on time averaging over short modified periodograms. IEEE Trans Audio and Electroacustics 1967;15(2):70–73.

[13] Richman JS, Moorman JR. Physiological time-series analysis using approximate entropy and sample entropy. Am J Physiol Heart Circ Physiol Jun 2000;278(6):H2039–49.

[14] Alcaraz R, Abásolo D, Hornero R, Rieta JJ. Optimal parameters study for sample entropy-based atrial fibrillation organization analysis. Comput Methods Programs Biomed Jul 2010;99(1):124–132.

[15] Alcaraz R, Rieta JJ. Sample entropy of the main atrial wave predicts spontaneous termination of paroxysmal atrial fibrillation. Med Eng Phys Oct 2009;31(8):917–922.

[16] Palus M, Hoyer D. Detecting nonlinearity and phase synchronization with surrogate data. IEEE Eng Med Biol Mag 1998;17(6):40–45.

[17] Alcaraz R, Sandberg F, Sörnmo L, Rieta JJ. Classification of paroxysmal and persistent atrial fibrillation in ambulatory ecg recordings. IEEE Trans Biomed Eng May 2011; 58(5):1441–9.

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