Noise and Spatial-resolution Effect of Electrode Array on Rotor Tip Location during Atrial Fibrillation: A Simulation Study

Miguel A Becerra[1], Juan Murillo-Escobar[1-2], Laura C Palacio[2], Catalina Tobón Zuluaga[2]

[1]Institución Universitaria Salazar y Herrera, Medellín, Colombia
[2]Instituto Tecnológico Metropolitano, Medellín, Colombia

Abstract

Atrial fibrillation (AF) is the most common arrhythmia in clinical practice. Recently, a mechanism for maintaining the AF which consists of one or more rotors activating the tissue at high frequency has been proposed. Ablation is one of the treatments for AF whose effectiveness could depend on the localization of the rotor tip.

In a previous research, the approximate entropy (ApEn) was proposed as an effective rotor tip detection system. However, this system was validated with an array of 22500 electrodes providing one noise-free simulated electrogram per electrode, which can be considered as a system distant to the reality. In this work, three analyses from simulated electrograms obtained from 2D model of human atrial tissue under chronic AF conditions for rotor tip detection are presented. The first one with noise-free, the second one with noise of real electrograms (NoRE), and the third one is done by applying the Kalman filter (KF) on the simulated electrograms with NoRE. In each case, the effect of the dimension of electrodes array is analyzed with relationships of equidistant reduction rows-column from 2-2 to 6-6. This comparison showed that the noise has a greater negative effect than the one generated by the decrease of resolution in electrodes array, and despite of the acceptable Kalman filter's performance for increasing the SNR significantly, the accuracy is lower than the results obtained with electrograms with NoRE but adequate for locating the rotor tip.

1. Introduction

The Atrial fibrillation (AF) is supraventricular arrhythmia and its prevalence is close to 2.5% [1]. AF ablation has the objective to stop or prevent the AF suppressing the triggers and modifying the arrhythmogenic substrate [2]. The most common AF ablation procedure consist of the electrical insolation of the pulmonary veins [3], although its effectiveness is 80% after 1.3 intervention per patient and the 30% of them need posterior use of antiarrhythmic drugs [4]. Also, there exists a high risk of AF recurrence [2], but there is not a mechanism to define it. However, common possible causes of AF recurrence are considered as follows: the electrical reconnection of the pulmonary veins, activation of tissue at high frequency by one or more rotors, and the effect of AF triggers located externally to the pulmonary veins [2].

Based on the above mentioned causes, the successful use of these procedures is highly related to the correct location of the rotor tips from electrograms with simple and double potentials electrograms and complex fractionated atrial electrograms (CFAE). These CFAE are low-voltage signals and they present highly fractionated potential with two or more deviations [5], but nowadays there is not a clear explanation about the cause of CFAE during AF.

Thus, several researches have been conducted to develop systems for the rotor tip location. The dominant frequency (DF) has been widely reported as an approach for rotor tip identification, but its results are limited due to its temporal variability [6]. Besides, a system based on Approximate Entropy (ApEn) was proposed in [7] showing a successful performance in the identification of rotor tips. However, these systems have just been tested on simulated environments and need high resolution electrode array.

We proposed to study the noise and the spatial resolution effect of electrode array on systems based on ApEn and DF used to locate rotors tip, for that we realize three analysis, the first one is carried out with noise-free simulated electrograms, the second one is executed with simulated electrograms with noise of real electrograms (NoRE), and the third one is done by applying the Kalman filter on the simulated electrograms with NoRE. In each case, the effect of the dimension of electrodes array is analyzed with relationships of equidistant reduction rows-column from 2-2 to 6-6 on a 2D model of human atrial tissue under chronic AF conditions.

2. Materials and methods

2.1. Approximate entropy (ApEn)

The ApEn is a measurement of the complexity and irregularity of a signal. The ApEn is a set of measurements of system complexity closely related to the entropy [8].

Mathematically ApEn is computed as [8], [9]:

i) X_N is a time series with N data points as follow:

$$X_N = [X_1, X_2 \dots X_N] \quad (1)$$

ii) $(\vec{X}_i)$ is a vector composed by m points:

$$(\vec{X}_i)_m = [X_i, X_{i+1} \dots X_{i+m-1}],\ (\vec{X}_i)_m \in X_N \quad (2)$$

iii) The distance between the vectors $(\vec{X}_i)$ and $(\vec{X}_j)$ is calculated as follow:

$$d[(\vec{X}_i), (\vec{X}_j)] = \max_{k=1,2\dots m} \left|(\vec{X}_{i+k-1}) - (\vec{X}_{j+k-1})\right| \quad (3)$$

iv) N_i^m is the number of $(j = 1 \dots N-m+1,\ j \neq i)$ that for a given $(\vec{X}_i)$ satisfied $[(\vec{X}_i), (\vec{X}_j)] \leq r$, where r represents the tolerance parameter.

v) Estimate the frequency of similar patterns:

$$C_i^m(r) = \frac{N_i^m}{N-m+1} \quad (4)$$

vi) The average of the natural logarithm of $C_i^m(r)$ is computed as follow:

$$\phi^m(r) = \frac{1}{N-m+1} \sum_{i=1}^{N-m+1} \ln C_i^m(r) \quad (5)$$

vii) The ApEn is calculated using the equation (6):

$$ApEn(m, r, N) = \phi^m(r) - \phi^{m+1}(r) \quad (6)$$

2.2. Kalman filter

The Kalman filter is an adaptive filter technique, commonly used in signal denoising and data fusion application. Kalman filter algorithm consists in two stages: the time update or prediction and the measurement update or correction [10].

The time update consists in predicting $\hat{x}$ at the stage k and the covariance matrix P_k, as is showed in the equation (7) and (8), where u_k is the control input vector, B_k is the control input matrix, F_k is the state transition matrix and finally Q_k is the process noise covariance matrix [11].

$$\hat{x}_k = F_k \hat{x}_{k-1} + B_k u_k \quad (7)$$

$$P_k = F_k P_{k-1} F_k^T + Q_k \quad (8)$$

The correction stage consists in improving the prediction realized in the previous stage, using the equations (9) and (10), Z_k represents the measurement, H_k is the transformation matrix and K_k is the Kalman gain [12].

$$\hat{x}_k = \hat{x}_k + K_k(Z_k - H_k \hat{x}_k) \quad (9)$$

$$P_k = P_k - K_k H_k P_k \quad (10)$$

The Kalman gain is calculated as follow:

$$K_k = P_t H_k^T (H_k P_k H_k^T + R_t)^{-1} \quad (11)$$

The noise measurement is assumed to be zero, that means white Gaussian noise and its covariance is R_t.

2.3. 2D model of simulated AF

The 2D model used in this study is made up of simulated atrial human tissue of 6 x 6 cm. On this model a permanent AF is simulated where 22500 EGMs were obtained from the model through virtual electrodes distributed over the surface of the model to a 400 µm distance among them. The model provides simple and double potentials of EGMs and CFAEs which lasted 5 seconds each one. It allowed generate a simulation of the rotor tip location which is showed in the Figure 1.

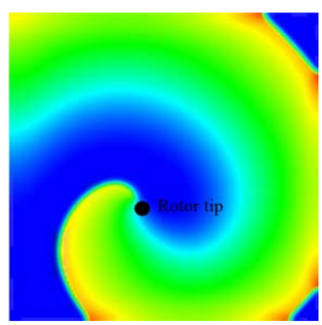

Figure 1. Simulated atrial human tissue

2.4. Proposed procedure

According to the Figure 2, the simulated EGM signals were added with noise of one real EGM signal and with simulated Gaussian White Noise in order to approximate the simulated signals to real conditions. In addition, the resolution of the electrode number per area was reduced in different proportions according to relationships of equidistant reduction rows-column from 2-2 to 6-6 equivalent to reduction between 75% and 97.2% of the total electrodes in the array. The rotor tip location was determined applying an ApEn algorithm to noise-free simulated electrograms and simulated electrograms with NoRE. Then, the EGM signals with NoRE were filtered using Kalman filter in order to reduce the noise and once again the rotor tip location was assessed using the ApEn algorithm. Finally, the performance of the procedure was obtained using the Euclidian distant to the real rotor tip location.

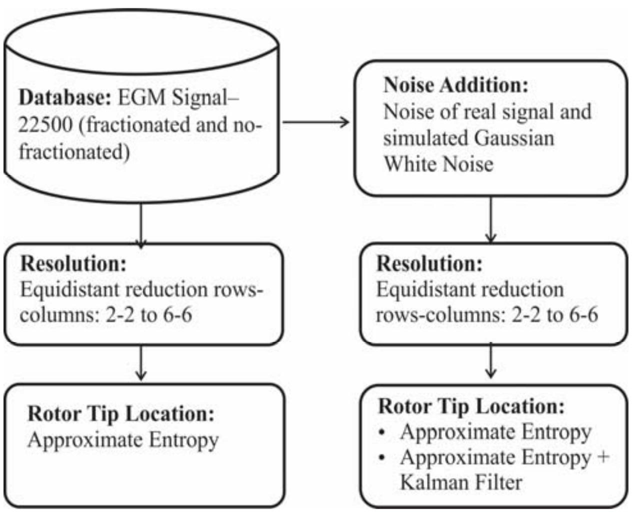

Figure 2. General proposed procedure

3. Results and discussion

Table 1 shows the error for rotor tip location based on the distance in millimeters (mm) between the known rotor tip position of 2D model and those predicted by ApEn algorithm using different spatial resolutions over noise-free simulated electrograms, simulated electrograms with NoRE and filtered EGM signal with NoRE using Kalman Filter. The signal to noise ratio (SNR) of the simulated electrograms with NoRE was 16.2 ± 1.1 dB. The error of rotor tip location was calculated for the resolution {1-1, 2-2,…,6-6}, obtaining the mean of error of 0.811 mm for the EGM without noise, 28.73 mm for EGM with noise and 6.5 mm for the filtered EGM reducing a 77.4% the error when the kalman filter was applied. The Figure 3 shows three different moments: on the left, the rotor tip location using ideal EGM, in the second image, the results obtained with EGM signals with noise which is completely distorted and on the third image the results of the rotor tip location using kalman filter, which demonstrated a high noise reduction.

Table 1. Spatial resolution and noise effect in rotor tip location.

Reduction	ERROR		
	Free noise [mm]	**Noise [mm]**	**Filtered [mm]**
1_1	0	31.5	5.9
2_2	1.26	38.5	5.9
3_3	0.89	28.8	5.9
4_4	0.56	38.35	7
5_5	1.6	6.4	8.4
6_6	0.56	28.8	5.9
Mean	0.81	28.73	6.5

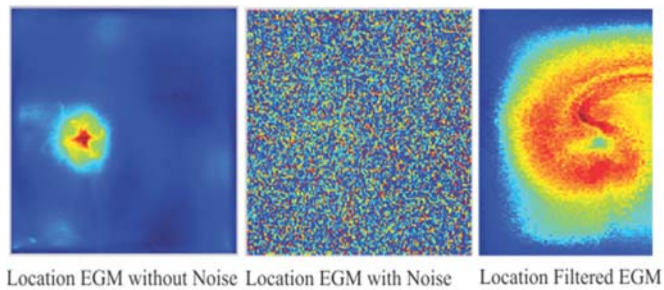

Figure 3. Tip rotor location

4. Conclusion

In this paper, the noise effect on the EGM signals and electrodes resolution for detecting rotor tip analysis was carried out by showing that the accuracy on the location of the rotor tip, based on approximate entropy algorithm, is negatively affected by the electrodes resolution.

In addition, the noise generated a decreasing of the average of accuracy in around 28% regarding to the signal without noise, independent of the resolution, showing that the approximate entropy algorithm is very sensitive to the noise. Nevertheless, when the Kalman Filter was applied, the negative effect was attenuated increasing the SNR. In spite of this increase, it was necessary to improve the SNR for obtaining a major location system. In this sense, applying the extended Kalman filter or another nolinear filter is proposed as future work and additionally using the IDW (Inverse Distance Weighted) technique as a method when the resolution is low in order to fill the holes presented in the electrodes matrix and to increase the resolution.

Acknowledgements

This work was supported by the Research Center of the Instituto Tecnológico Metropolitano ITM of Medellin Colombia and by the Research Center of the Institucion Universitaria Salazar Herrera of Medellin Colombia, under grant number 250

References

[1] Schnabel RB, Wilde S, Wild PS, Munzel T, Blankenberg S. Atrial fibrillation: its prevalence and risk factor profile in the German general population. Dtsch Arzteb Int 2012; 109:293–9.

[2] Calkins H, Kuck KH, Cappato R, Brugada J, Camm J, Chen SA, Crijns HJG, Damiano RJ, Davies DW, DiMarco J, Edgerton J, Ellenbogen K, Ezekowitz MD, Haines D E, Haissaguerre M, Hindricks G, Iesaka Y, Jackman W, Jalife J, Jais P, Kalman J, Keane D, Kim YH, Kirchhof P, Klein G, Kottkamp H, Kumagai K, Lindsay BD, Mansour M, Marchlinski FE, McCarthy PM, Mont JL, Morady F, Nademanee K, Nakagawa H, Natale A, Nattel S, Packer D L, Pappone C, Prystowsky E, Raviele A, Reddy V, Ruskin JN, Shemin RJ, Tsao HM, Wilber D. HRS/EHRA/ECAS Expert Consensus Statement on Catheter and Surgical Ablation of Atrial Fibrillation: recommendations for patient selection, procedural techniques, patient management and follow-up, definitions, endpoints, and research trial design. Europace. 2012; 14: 528–606.

[3] Pappone C, Santinelli V, Manguso F, Vicedomini G, Gugliotta F, Augello G, Mazzone P, Tortoriello V, Landoni G, Zangrillo A, Lang C, Tomita T, Mesas C, Mastella E, Alfieri O. Pulmonary vein denervation enhances long-term benefit after circumferential ablation for paroxysmal atrial fibrillation. Circulation 2004; 109: 327–34.

[4] Cappato R, Calkins H, Chen SA, Davies W, Iesaka Y, Kalman J, Kim YH, Klein G, Natale A, Packer D, Skanes A, Ambrogi F, Biganzoli E. Updated worldwide survey on the methods, efficacy, and safety of catheter ablation for human atrial fibrillation. Circ Arrhythm Electrophysio 2010; 3: 32–8.

[5] Nademanee K, Lockwood E, Oketani N, Gidney B. Catheter ablation of atrial fibrillation guided by complex fractionated atrial electrogram mapping of atrial fibrillation substrate. J Cardiol 2010; 55:1–12.

[6] Habel N, Znojkiewicz P, Thompson N, Müller JG, Mason B, Calame J, Calame S, Sharma S, Mirchandani G, Janks D, Bates J, Noori A, Karnbach A, Lustgarten DL, Sobel B E, Spector P. The temporal variability of dominant frequency and complex fractionated atrial electrograms constrains the validity of sequential mapping in human atrial fibrillation. Heart Rhythm 2010; 7: 586–93.

[7] Orozco-Duque A, Ugarte J. Approximate entropy can localize rotors, but not ectopic foci during chronic atrial fibrillation: A simulation study. Comput 2013: 903–906.

[8] Pan Y-H, Wang Y-H, Liang S-F, Lee K-T. Fast computation of sample entropy and approximate entropy in biomedicine. Comput. Methods Programs Biomed 2011; 104: 382–96.

[9] Guo L, Rivero D, Pazos A. Epileptic seizure detection using multiwavelet transform based approximate entropy and artificial neural networks. J. Neurosci. Methods 2010; 193(1): 156–63.

[10] Vullings R, de Vries B, Bergmans JWM, An adaptive Kalman filter for ECG signal enhancement. IEEE Trans. Biomed. Eng. 2011; 58(4): 1094–103.

[11] Grewal S, Angus PA. Kalman Filtering: Theory and Practice Using MATLAB, 2nd ed. 2001; 5: 1 – 395.

[12] Faragher R. Understanding the basis of the Kalman filter via a simple and intuitive derivation. IEEE Signal Process. Mag 2012: 128–132.

Address for correspondence.

Miguel A. Becerra
Cra 70 No 52-49
migb2b@gmail.com