Does Mapping Catheter Geometry and Location Affect AF Driver Detection? A Simulation Study

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Abstract

In atrial fibrillation the correct identification of both presence and location of rotors during the ablation procedure could support the physician to optimize therapy administration. In this study we developed a tool that allows testing the capability of mapping catheters of detecting AF drivers with different shapes and in different acquisition conditions. Wave propagation was obtained using a monodomain implementation and a modified Courtemanche model. Two commercial catheters were simulated (Advisor™ HD Grid and PentaRay®). Our framework allowed the acquisition of the signal in unipolar mode at and to assess the effect of the influence of catheter inter-electrode spacing,coverage and endocardium-LA wall distance for rotor detection. In contact with the wall and within 1mm distance from the real core all the configurations allowed a correct detection of the rotor, irrespective of geometry, coverage and inter-electrode distance. Increasing the inter-electrode distance causes the incapability of rotor detection at a closer distance from the LA wall in the HD grid.The tool was effective in assessing how catheter geometry and specific parameters affect its capability to detect rotors. In the future, other catheter morphologies and different design parameters and acquisition conditions will be investigated.

1. Introduction

Cardiovascular diseases are the leading cause of death in Western countries [1] and considering arrhythmias atrial fibrillation (AF) is one of the most common in elderly patients and rising given the ageing of the population [2].

Today catheter ablation is the designed therapeutic approach for atrial fibrillation after the failure of antiarrhythmic drug treatment. Such therapy is targeted to the drivers triggering or sustaining AF, including re-entrant waves (rotors). However, the hypothesis of "rotors" is still controversial, and even though the capabilities of the novel mapping technologies are increasing the problem of comparing the results and the different reconstruction obtained still exist. Still, the correct detection and tracking of rotational sources which sustain the high frequency activation of myocardial tissue are of paramount importance for the planning of the ablation procedure.

Since in clinical practice rotor detection is achieved from the analysis of the electrograms obtained using multi-electrode mapping catheters, in this study we developed a tool which allows testing the capability of such catheters of detecting AF drivers. By applying computer simulations, we investigated how inter-electrode spacing, catheter coverage and endocardium-LA wall distance influence rotor detection.

2. Methods

2.1. Monodomain tissue simulation

In the proposed approach we considered a simulated bidimensional patch of myocardial tissue of size 50mm x 50mm. The resolution of the grid is 0.25mm obtaining a 201x201 grid of tissue samples. AF was obtained using a modified Courtemanche model [4] which accounts for AF related ionic remodelling [5]. For triggering the spiral wave, we have applied a stimulus (stimulus current amplitude -2000pA with duration=1ms) at t=0 to the bottom line of the grid and an extrastimulus of the same amplitude applied at t=105ms (with duration=0.25ms) on the left bottom corner (25x25 cells) of the simulated tissue. The voltage of each point of the grid was then sampled at a 2 kHz frequency, and local phase and activation times were computed.

On the simulated grid the activation wave geometry

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was parameterized and used to accurately pinpoint the location of the rotor tip throughout the whole simulation time.

2.2. Catheter geometry and electrogram computation

For this project two different geometries belonging to real catheters used in clinical practice were used. The Advisor™ HD Grid is a grid catheter of 16 electrodes (4x4), with standard inter-electrode spacing of 3mm. The PentaRay® is a star-shaped electrode with five arms of 20 electrodes, with 4mm between electrodes in each segment.

To assess the capability of the catheter to correctly detect and trace the phase singularities, the barycentre of the electrode was translated on the mean position of the simulated rotor which is known as our ground truth.

For each electrode, the voltage was computed using the following formula:

$$egm_{unipolar} = \sum_i \frac{\Delta V_{m_i}}{d_i^2 + z_0^2}$$

where $\Delta V_{m_{i_{xx}}}$ is the Laplacian of the voltage computed in each point of the grid, d^2 is the squared distance on the plane between the electrode and the point of the grid, while z_0 is the wall distance, which was set to 0.25mm in the "contact" case to avoid numerical singularities caused by the discretization of the myocardial tissue .

To assess the sensibility of the rotor detection algorithm, we changed the grid-like inter-electrode distance (3-6mm), the number of electrodes (16-36-64), herein increasing the coverage of the catheter and the distance from the wall (0-1-2-3mm), which models the detachment of the catheter from the atrial wall tissue during the acquisition of the electrograms. For the star-shaped electrode the spacing between electrodes was changed (2-4mm), it was rotated by 36° degrees clockwise, and at varying wall distances (0-1-2-3mm).

To simulate different contact conditions, different distances (z_0) for each spline of the HD Grid catheter were tested using three different setups:

- central splines at 1mm and lateral ones in contact;
- lateral splines at 1mm and central ones in contact;
- first two splines in contact, third spline at 2mm, and fourth spline at 3mm.

From the electrograms, the local phase was computed, and the rotor tracking algorithm described extensively in [3] was applied to extract the phase singularities (PS).

2.3. Rotor metrics

Taking into consideration only the longest rotor, for each detected PS belonging to it, the barycentre of the electrodes which contain the smallest closed loop was used to place a bidimensional gaussian distribution, of standard deviation equal to 1.5mm and fill a phase singularity density map. The phase singularity density is the function of the position (x, y), with the following formula:

$$PSd(x,y) = \frac{1}{2\pi\sigma^2} \sum_{i=1}^{N} e^{-\frac{(x-x_{PSi})^2+(y-y_{PSi})^2}{2\sigma^2}}$$

where x_{PSi} and y_{PSi} are the coordinates of the i-th PS, and σ set to 1.5mm. The standard deviation choice was made considering the 3mm grid of the HD Grid catheter, in this way the density map function does not have gaps when phase singularities are detected in neighboring regions.

For the assessment of the quality of rotor detection from the afore-described density map of the rotor phase singularities was computed, and a series of metrics were evaluated:

- value of the density peak;
- standard deviation of the phase singularities distribution;
- peak-to-peak distance between ground truth and estimated rotor.

The value of the peak of density is meaningful to assess the length and stability of the rotor. The standard deviation of the distribution gives both information on the size of the area covered by the movement of the rotor, and on the ability to accurately pinpoint the core of the rotor. The peak-to-peak distance assesses the spatial error of the algorithm using the different parameters with respect to the known ground truth. Another index evaluated to assess the performance of the catheter geometry and the different parameter was the overall length of the detected rotor.

3. Results and discussion

An illustrative frame of the simulated rotor phase map is shown in Figure 1 (top-left panel), together with the cumulative rotor tip trajectory density (bottom-left panel).

All the results are reported in Table 1. When a perfect contact between the catheter and the cardiac tissue was simulated all the configurations allowed a correct detection of the rotor, irrespective of geometry, coverage, and inter-electrode distance. As a matter of fact, the estimated position of the rotor core (i.e. the position of the peak of the trajectory density) was exactly the real one or only 0.25mm far from it.

In the grid-like catheter geometry increasing the inter-electrode distance caused the incapability of rotor detection at a closer distance from the LA wall. In this condition, the peak density increased as more of the singularities fell in the region of the four center-most electrodes when the catheter was in contact with the tissue. At a wall distance of 3mm the electrograms

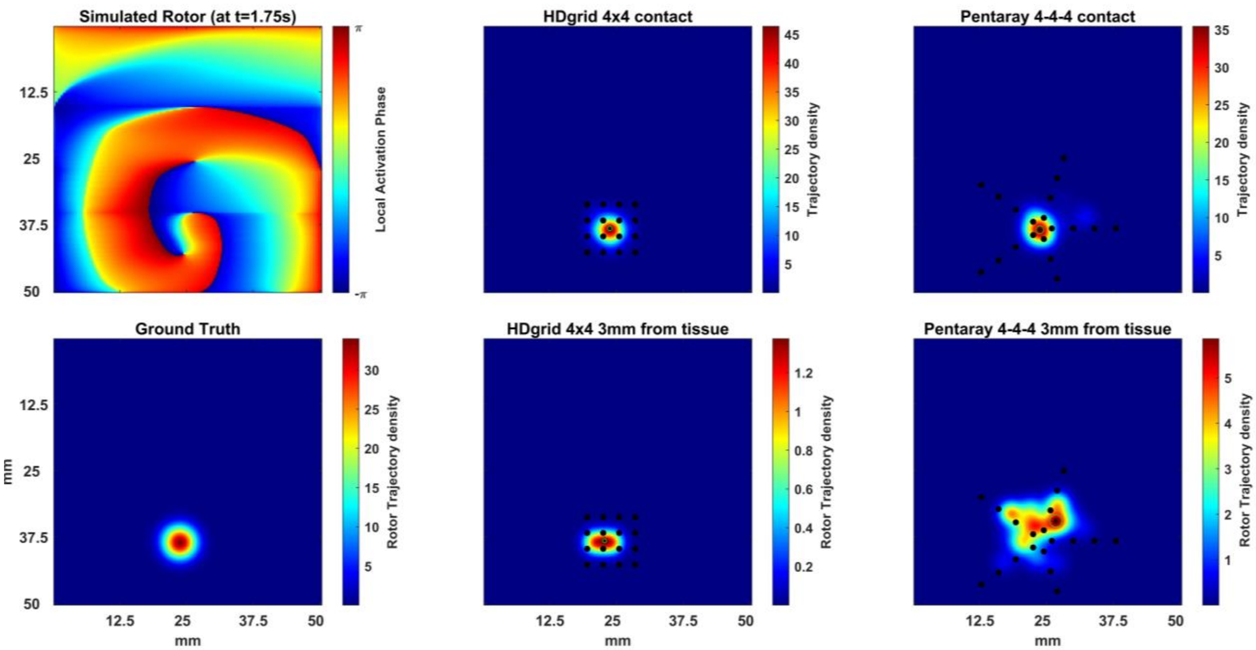

Figure 1. Simulated monodomain tissue local activation phase (top left panel), and phase singularities density maps for the ground truth (bottom left panel), HD Grid and PentaRay cathethers both in contact (middle and right panels, 1st row) and at 3mm wall distance (middle and right panels, 2nd row).

Table 1. Simulation parameters and resulting indexes derived from the phase singularity maps for ground truth, HD Grid and PentaRay catheters, varying coverage (number and spacing between electrodes) and atrial wall distance.

Catheter Configuration	Inter-electrode distance (mm)	Distance from the atrial wall (mm)	Peak of density (PS/mm^2)	Standard deviation (mm)	Peak to peak distance (mm)	Rotor lifetime (s)
Ground Truth	-	-	544	8.23	-	7.75
	3		743	1.78	0	7.71
HD Grid 4x4	6		1078	0.6	0.25	7.7
HD Grid 6x6	3	0	741	1.8	0	7.71
HD Grid 8x8	3		512	1.55	0	4.94
HD Grid 4x4	3	3	22	1.47	1	0.25
	6	3	18	4.29	0.25	0.28
missing contact splines						
HD Grid central splines	3	1	439	2.69	0.25	7.72
HD Grid lateral splines	3	1	790	1.56	0	7.71
HD Grid 3rd and 4th splines	3	2/3	620	1.85	0.56	6.49
PentaRay	4-4-4	0	567	2.9	0	7.71
		3	93.7	4.66	3	3.56
	2-2-2	0	963	0.76	0.25	7.72
		3	260	2.96	0.5	5.3
PentaRay rotated	4-4-4	2	301	4.37	0.25	7.72
	2-2-2	2	546	2.33	0.5	7.72

became too smoothed to consistently detect the activation, and phase singularities were lost, resulting in a sharp fall of all the meaningful indexes, even though the localization of the rotor tip is still near the ground truth.

Moreover, testing the different contact conditions showed that the algorithm was robust with only small changes in the rotors lifetime.

In the PentaRay-like configuration, independently from the inter-electrode distance, the rotor detection failed at 3mm endocardium-catheter distance. Of further interest is the fact that the asymmetry of such catheter, considering the maximum rotation of 36° degrees results in rotation-dependence in the rotor detection, which is consistent with the fact that since the real rotor tip is moving in one configuration it is easier for it to cross the region enclosed by the five center-most electrodes and lose the tracking.

4. Conclusion

The developed tool allowed to simulate different catheters, being able to reproduce both commercial high-resolution catheters and catheters in which parameters such as number of electrodes, inter-electrodes distance and endocardium-catheter distance were changed.

The main message of our findings is that the inter-electrode distance is critical for the rotor detection when the distance between the catheter and LA wall increases for both the tested catheter shapes. The higher resolution in the central part of the catheter also seems to underlie the better performance of the PentaRay 2-2-2 compared with the HD Grid 4x4 at 3mm from LA wall. Moreover, both the PentaRay 4-4-4 and the HD Grid 4x4 at both tested interelectrode distances (3mm and 6mm), lose the correct detection by increasing catheter-LA distance.

Obviously pour study has several limitations; in particular, we presented simulations for a single scenario of a rotor area without additional wave breaks; this can limit our ability to extrapolate quantitatively the results to more complex fibrillatory wave propagation scenarios. In addition, the reliability of the proposed approach cannot be easily assessed without a comparison with either experimental data or a more sophisticated computational model. Unfortunately, real-life data cannot be used for the evaluation of the proposed tool not being known the actual location of AF drivers.

To conclude, the computational framework we developed is based on realistic catheter shapes designed with parameter configurations that resemble clinical settings. It allowed the simulation of both commercial high-resolution catheters and catheters in which parameters such as the number of electrodes, inter-electrodes distance, and endocardium-catheter distance were changed. Results showed it is well suited to investigate how mapping catheter geometry and location affect AF driver detection, therefore it is a reliable tool to design and test new mapping catheters. In addition, it provided visual feedback about the spatial density map of the rotor tip trajectory, a proposed marker of the presence of an AF source. In the future, other catheter morphologies and different parameters/conditions will be investigated.

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