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Development of a Rotor-Mapping Algorithm to Locate Ablation Targets During Atrial Fibrillation

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Abstract

Catheter ablation therapy involving isolation of pulmonary veins (PVs) remains the cornerstone procedure to treat AF. However, due to the sub-optimal success rates of PV isolation, there is a need for new ablation techniques to locate AF ablation targets known as rotors, outside of the PVs. In this paper, we developed a novel rotor-mapping algorithm that uses a conventional diagnostic catheter, Lasso, to locate a rotor source. The algorithm, called the Region of Rotor (ROR) Mapping, utilizes the characteristics of local bipolar electrograms to navigate the catheter's iterative placements while generating a map, overlaid on the atrial anatomy, that displays the potential rotor region. We evaluated the developed ROR mapping algorithm using a 2D simulation of AF on a tissue with heterogeneous conduction properties. The results demonstrated a significant success rate of 93% in accurately locating the region of the rotor with a mean distance of 1.4mm from the ground truth trajectory. The algorithm could play a critical role in mapping non-PV AF ablation targets and improving the outcome of AF ablation.

Keywords

atrial fibrillation; AF ablation; rotor-mapping; non-PV ablation targets; intra-atrial electrograms

I. Introduction

Atrial fibrillation (AF) is characterized by irregular beating of the atria due to disorganization of electrical signals. AF is a major cause of stroke and affects more than 2.7 million people only in the US [1]. Catheter ablation therapy, which involves electrical isolation of the pulmonary veins (PVs), is the most commonly used treatment for AF. This procedure attempts to block the ectopic signals originating from PVs that are believed to be triggering the arrhythmia. However, currently this procedure has demonstrated only suboptimal outcomes with a success rate of 40%–60%. Ablation of AF-sustaining sources, known as rotors, outside of PVs has been shown to improve the success rate [2].

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The present technology to locate rotors, called the Focal Impulse and Rotor Modulation (FIRM), is based on a contact basket catheter which is placed inside the atrium to simultaneously collect and analyze 64 unipole electrograms. However, these baskets even at their highest resolution suffer from poor electrode contact and insufficient spatial resolution. In this paper, we developed a novel algorithm to map the region of rotor (ROR) using a multi-pole diagnostic catheter. These catheters are commonly used for electro-anatomic mapping of the atria during AF ablation and provide a high-resolution map of a small area of the atria. In our previous work [3], we showed that if the electrograms collected from the iterative placements of these catheters are analyzed properly, they can be used to locate the ROR. In this paper, we present a novel ROR mapping algorithm based on the iterative placement of a 20-pole diagnostic catheter, known as Lasso. The paper continues as follows. In Section II, we explain the 2D simulation of AF that was used as a testbed to evaluate the developed ROR mapping algorithm. The developed algorithm is presented in Section III. Our evaluation results are provided in Section IV and the paper is concluded in Section V.

II. Materials

A. Rotor Simulation

We employed a computer simulation to generate a $10\text{ cm} \times 10\text{ cm}$ atrial tissue with a spatial resolution of 0.025 cm and time steps of 0.05 milliseconds. We used the Nygren *et al.* human atrial cell model [4], which is based on average voltage-clamp data recorded from isolated single myocytes from typical bulk atrial tissue. To model fibrosis, thick collagenous septa were introduced by removing electrical connections between neighboring myocytes oriented along an assumed fiber orientation (horizontal) and uniformly distributed throughout the tissue. The septa lengths varied according to a Poisson distribution with an average length of 2.5 mm and affected 20% of the tissue. A single rotor was initiated on the tissue and it was sustained for the full duration of the simulation [5].

B. Lasso Catheter Simulation

A 20-pole Lasso catheter (Biosense Webster) with 15 mm diameter and $4.5\text{--}14.5\text{ mm}$ electrode spacing was simulated. First, unipolar electrograms were simulated by following Bueno-Orovio *et al.* [6]. Next, ten bipolar electrograms were calculated from the pairs of the 20 unipolar electrograms by subtracting the unipolar electrograms. These bipolar electrograms were further processed by the mapping algorithm.

III. Region of Rotor Mapping Algorithm

We developed a ROR mapping algorithm to locate non-PV AF ablation targets, known as rotors. The algorithm starts with an arbitrary placement of the Lasso catheter and guides the iterative movements of the catheter based on the characteristics of the 10 bipole electrograms at every placement. As the catheter is guided, the algorithm updates a ROR map.

The algorithm stops the mapping once a set of criteria is satisfied and reports the final ROR map and its center point as the detected region of the rotor on the atrial tissue and the potential coordinates of the rotor core, respectively. As shown in Fig. 1, the ROR mapping

algorithm consists of the following steps: electrogram analysis, mapping of the ROR, navigation of the catheter, and the stopping criteria.

A. Electrogram characteristics computation

At every placement of the Lasso catheter, local activation times of each bipole electrogram are identified as the time of the maximum negative deflection. A customized program [3] was developed to identify the activation times associated with the same wavefront as one cycle (Fig. 2B). Cycle length (CL) is determined as the time delays between the activations in two adjacent cycles.

Two characteristics are computed from the detected cycle: (1) principal wave direction (PWD) and (2) conduction delay ratio (CDR). The PWD estimates the direction of the propagating AF wave source relative to the catheter's current location. The PWD is determined as a vector starting from the catheter center point and pointing to the first activated bipole. The PWD with angle θ at catheter placement C_k is calculated using the following equations:

$$\vec{PWD} = P_1 - P_0 = re^{j\theta} \quad (1)$$

$$P_0 = d(O, C_k)e^{j\theta}C$$

$$P_1 = d(O, Bipole_k)e^{j\theta_k},$$

where C_k and $Bipole_k$ are the coordinates of the catheter center and first activated bipole with respect to the origin O . The function $d(a, b)$ calculates the Euclidean distance between points a and b . The value of r is the radius of the catheter (i.e., $r = 0.75mm$). An example with the PWD of $\theta = 276deg$ is shown in Fig. 2A.

CDR is calculated as the ratio of the total conduction delay to CL. The total conduction delay is determined as the absolute value of the sum of all the conduction delays between two adjacent bipoles. The CDR provides a measure of the time taken for the rotor wavefront to propagate through the tissue area where the catheter is placed relative to the time taken for the rotor to complete one rotation with reference to that catheter location.

B. Mapping of the ROR

The initial ROR map before placing a catheter is the entire tissue. After the first catheter placement, the ROR that contains area of $\pm\pi/2$ with the PWD as the basis vector (i.e., from $\theta + \pi/2$ to $\theta - \pi/2$) is kept and the remaining area is excluded from the ROR. For example, in Fig. 2A, the PWD direction for the catheter placement at C_1 is towards bipole number six (the blue circle in Fig. 2B) and the gray area in Fig. 2A was excluded from the ROR (i.e., the clear area). Note that the PWD is almost towards the rotor trajectory (shown in Fig. 2A). This procedure of mapping the gray area is repeated at every catheter placement until the constructed map delineates the ROR. A final ROR map after placing the catheters in locations C_1 to C_4 is shown in Fig. 2C. The localized rotor point is also shown in the figure.

It can be seen that the point lies on the rotor trajectory and the final ROR map includes most of the rotor trajectory.

There is only one exception to this updating procedure and that is when the CDR value at a catheter placement is 0.6. As shown in our previous work, the electrogram patterns associated with high CDR values provide a rotational pattern around the catheter bipoles [7], and hence the first activated bipole may not reliably estimate the direction of the wave propagation. Hence, the algorithm is designed not to update the ROR map when CDR = 0.6. Other than this exception, the map is updated according to the direction of the PWD as described above.

C. Navigation of the catheter

The decision on the subsequent placement of the catheter is made as follows. Depending on the ROR area, ROR being greater or smaller than four times the catheter area (A), one of the two strategies is followed.

- PWD-based navigation if $ROR > 4A$
- Centroid-based navigation if $ROR \leq 4A$

1) PWD-based Navigation: The catheter is guided to half the maximum distance (d_{max}) between the catheter current catheter center and the boarder of ROR map along the PWD direction θ . The example shown in Fig. 2A guides the catheter from C_1 to C_2 , which is in the middle of d_{max} . This procedure for a current catheter placement C_k with C_{kx} and C_{ky} Cartesian coordinates is given by the equation below.

$$C_{k+1} = (C_{kx} + r\cos\theta, C_{ky} + r\sin\theta) \quad (2)$$

where $r = \frac{d_{max}}{2}$.

2) Centroid-based Navigation: This type of navigation consists of two steps. Fig. 3 illustrates the method of centroid-based navigation. In step 1, the intersections between all the previous PWD vectors θ_1 to θ_k are determined and the average location of all the intersections that are inside the current ROR map (green circles) is calculated as the centroid location (green square). In step 2, the subsequent catheter placement is determined as half the maximum distance d_{max} between the centroid and the ROR boundary in all directions (not restricted to PWD). In Fig. 3, the intersections inside the ROR are shown in dark green circles, and the centroid of these intersections is the light green square. Hence half of d_{max} is the location C_7 from the centroid.

The centroid-based navigation is used to guide the catheter when $ROR \leq 4A$. Regardless of the size of the ROR area, there are two special cases that use this type of navigation. One scenario is when $CDR = 0.6$ at C_k . As explained earlier, the PWD, in such cases, may not reliably represent the rotor propagation direction. The other scenario is when the catheter movement will be small because of a small value of d_{max} (i.e., less than the catheter

diameter). In both cases, step 2 of the centroid-based navigation using the current catheter center as the centroid is employed.

D. Stopping criteria

After every time that the ROR is updated, the algorithm stops if one of two is satisfied.

- $ROR_k \leq A$
- $ROR_k - ROR_{k-1} \leq 0.1A \ \& \ ROR_k \leq 2A$

The first criterion implies that the ROR area is less than or equal to the catheter's area. The second criterion indicates that there has not been any significant changes to the ROR map between the current and previous catheter placement and the ROR area is small enough to stop the ROR mapping.

Once the ROR mapping algorithm is stopped, the final ROR map and its center point (the pink square in Fig. 2C) are provided as the region of the rotor and the location of the rotor core, respectively. Note that the pink square in Fig. 2C lies exactly on the rotor trajectory (shown in white).

IV. Results

We applied the ROR mapping algorithm to the simulated rotor with any of the locations on the atrial tissue as the initial catheter placement. The algorithm reports the final ROR map and its center point. The mapping process was reported unsuccessful if it did not stop within a fixed maximum number of catheter placements ($k = 25$ iterations in this study). This procedure was repeated for each of the grid locations ($N = 114,921$) on the discretized atrial tissue.

The results of the algorithm indicated that all the ROR mapping cases were successful meaning that all the $N = 114,921$ initial catheter placements stopped and reported a final ROR map before the maximum number of iteration $k = 25$ was reached. The average iterations for every radial distance from the rotor trajectory to the initial placements ($N = 114,921$) was analyzed (see Fig. 4). It showed that the average number of iterations required increased with distance from the initial catheter placement. However, the slope angle was negligible ($\theta_{slope} = 1.4\text{deg}$), implying that the average number of iterations was almost constant regardless of where the initial placement was. This demonstrates the optimal nature of the mapping algorithm in the context of number of iterations to arrive at a final ROR.

Next, we compared the final ROR map against the ground truth of the rotor trajectory. We calculated the percentage of the rotor trajectory that was inside the final ROR map for all the 114921 trials. Our analysis indicated that the final reported ROR maps contained on average $85.9\% \pm 15.9\%$ of the entire rotor trajectory and 97.3% of the ROR maps included at least 50% of the rotor trajectory. We also calculated different values of the rotor trajectory percentage as shown in Fig. 5; it can be seen that 95% of the final RORs included 55% of the rotor trajectory. This percentage was 75% when we considered the ROR maps that included 75% of the rotor trajectory.

We also investigated the localization accuracy of the algorithm. For this purpose, the shortest distances between the ROR center points and the rotor trajectory were determined. The mapping cases that resulted in a center point within 4mm (diameter of an RF ablation catheter) were labeled as true positive detections and the cases with a center point with a distance greater than 4mm distance from the rotor trajectory were labeled as false positives. This analysis indicated that 93% of all trials were true positives and successfully located the rotor.

Finally, we investigated the total number of catheter placements until the ROR was reported. On average, the algorithm took 9.8 ± 2.4 iterations to detect a final ROR map (see Fig. 4).

V. Conclusion

In this paper, we developed a novel algorithm to detect the Region of Rotor (ROR) by using the electrogram bipoles recorded from a conventional multi-polar diagnostic catheter. The algorithm consists of an iterative process that navigates the catheter on the atrial anatomy in order to map the ROR. We evaluated our algorithm using fibrotic atrial tissue and human AF simulations. The results of the algorithm demonstrated successful ROR detection in under 25 catheter placements with a success rate of 93%. The detected ROR map and the estimated location of the rotor core could have a significant role in identifying non-PV rotor sources during AF ablation and successful termination of AF. In addition to detecting the potential rotor sources, the developed algorithm provides the clinician with a visual feedback of the ROR map as the map is being generated. This could provide additional information for the clinician to control the catheter placements as needed. The implementation of the ROR mapping algorithm in 3D AF simulations will be studied in our future work.

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Fig. 1.
Overview of the developed rotor-mapping algorithm.

Fig. 2.

Mapping of the ROR: (A) The initial catheter placement C_1 and the ten bipoles indicated by numbers 1 to 10. The white path indicates the rotor trajectory. (B) The bipolar electrograms of the C_1 catheter placement. The dotted line corresponds to the time shown in A. (C) The final ROR map with the center point indicated by an asterisk. The gray areas in A and C indicate the non-ROR area and the remaining clear area indicates the ROR.

Centroid-based Navigation

Fig. 3.

Centroid-based navigation: The catheter centers from 1 to k iterations are indicated by C_1 to C_6 . The next location to move (C_7) is determined by centroid indicated by the green square and the farthest ROR boundary (connected by a dotted line). This light green square is the centroid of the points indicated by dark green circles, which are the intersections of the PWD vectors inside the ROR. The dotted line with arrows show the PWD extended from a magnitude of d_{max} , which forms intersections outside the ROR indicated in red circles.

Fig. 4.

Average iterations vs distance from the rotor: The plot shows the variation of the average iterations taken by the mapping algorithm with respect to the radial distance of the initial catheter placement from the rotor trajectory. The global average iterations and the corresponding distance is also indicated.

Fig. 5.

Percentage of rotor trajectory in final RORs: The percentage of algorithm runs (y-axis) that produced a final ROR which consisted of at least $x\%$ (x-axis) of rotor trajectory inside the ROR. It can be seen that 95% of trials produced final RORs that contained more than 50% of the rotor trajectory in it.