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Development of a Novel Probabilistic Algorithm for Localization of Rotors during Atrial Fibrillation

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Abstract

Atrial fibrillation (AF) is an irregular heart rhythm that can lead to stroke and other heart-related complications. Catheter ablation has been commonly used to destroy triggering sources of AF in the atria and consequently terminate the arrhythmia. However, efficient and accurate localization of the AF sustaining sources known as rotors is a major challenge in catheter ablation. In this paper, we developed a novel probabilistic algorithm that can adaptively guide a Lasso diagnostic catheter to locate the center of a rotor. Our algorithm uses a Bayesian updating approach to search for and locate rotors based on the characteristics of electrogram signals collected at every catheter placement. The algorithm was evaluated using a 10 × 10 cm $2D$ atrial tissue simulation of the Nygren human atrial cell model and was able to successfully guide the catheter to the rotor center in 3.37±1.05 (mean±std) steps (including placement at the center) when starting from any location on the tissue. Our novel automated algorithm can potentially play a significant role in patient-specific ablation of AF sources and increase the success of AF elimination procedures.

Index Terms

atrial fibrillation; catheter guidance; atrial rotor source; non-pulmonary vein ablation; bayesian modeling

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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 [1] and a serious health concern, thus making a critical field for research and development. Investigation of the sources of AF, and consequent development of electrical and pharmacological therapies, have been of great interest for decades. Catheter ablation therapy involving the isolation of pulmonary veins (PVs), called PV Isolation (PVI), is one of the most successful treatments for AF today. PVI aims to electrically isolate the PVs by cauterizing the tissue around the PV ostia using radio-frequency energy applied through an ablation catheter. This blocks the ectopic signals originating from PVs, which were found to be triggering the arrhythmia.

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Current ablation procedures also employ linear lesions at locations that are predetermined mainly based on anatomy. These procedures are supported by advanced software tools for reconstructing the 3D anatomy of the left atrium (LA) and many other sophisticated operations. Despite such advancements in procedure and the technology used in procedure, the success rate of catheter ablation is suboptimal. A major reason for the suboptimal success rate is that the current ablation methods do not address patient-specific arrhythmic sources. Clinical studies on the mechanisms behind human AF have revealed the presence of high-frequency spiral waves in LA regions outside the PVs [2], [3], [4]. Ablating these potential arrhythmic drivers, commonly called "rotors", could lead to significant improvement in the success rate, which has been evident from some human studies [5]. However, determining the location of rotors is a challenging task, and various approaches have been developed in the past to address it [6], [7], [8]. Once the rotor centers are found, ablation can be performed to terminate them.

We present a novel probabilistic method that uses a Bayesian updating technique to iteratively guide the catheter towards the center of a rotor. The developed algorithm, the first of its kind, allows the clinician to use a Lasso multi-pole diagnostic catheter to localize rotors without any additional cost or risk to the patient. The catheter could be placed initially at any arbitrary location on the tissue. The algorithm will then iteratively guide it to the rotor center using local information such as the 2D location and electrogram (EGM) characteristics. The accuracy of the estimates involved in the algorithm gradually increases with every iteration, thus minimizing the time taken to reach the center of rotor.

II. Methods

The proposed algorithm employs a Bayesian method to estimate the location of a rotor, as discussed in the following sections.

A. Rotor Simulation

We employed a numerical simulation to generate human atrial fibrillation data. A 10 cm × 10 cm 2D atrial tissue with a spatial resolution of 0.025 cm and sampling frequency of 500 Hz was simulated using the Nygren human atrial cell model [9]. A single stable rotor was initiated on the tissue and a 10-bipole Lasso catheter (Biosense Webster) with 15 mm diameter and 4.5-1-4.5 mm electrode spacing was simulated. The bipolar EGMs of the Lasso catheter were calculated from the unipolar EGMs which are the weighted sum of the Laplacian of the transmembrane potentials.

B. Discrete Search-space Definition

The 2D simulated tissue described earlier is considered as the bounded space for searching for the rotor center. First, this search space is discretized to form a 2D grid, as shown in Fig. 1. Now, each grid location is represented by 2D coordinates (x, y). Therefore, the center of rotor could be present at any grid location. The center of the Lasso can be placed anywhere on the grid to collect the bipolar EGMs.

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C. Characterization of Simulated Electrograms

At any location of recording, the following local EGM characteristics are calculated according to their definitions:

1) First Activated Bipole—The First Activated Bipole (FAB), denoted by Φ, is a characteristic that refers to the label number of that bipole of the catheter encountering the earliest activation due to the rotor wavefront. The label numbers of bipoles are considered to be 1 through 10 starting from the farthest end of the Lasso.

2) Rotor Propagation Ratio—Rotor Propagation Ratio (RPR), mathematically denoted by τ, is the ratio of the EGM characteristics "Total Conduction Delay" and "Cycle Length", which are defined as follows:

Total Conduction Delay (TCD) is the sum of the time delay between activations of adjacent bipoles that belong in the same cycle. Cycle Length (CL) is the average of time delays between two activations in the same bipole, but belong in adjacent cycles.

Hence, RPR (*i.e.*, τ) is defined as the ratio of TCD to CL. Intuitively, the RPR provides a metric for the time taken for the rotor wavefront to propagate through the catheter placed at a particular location, relative to the time taken for the rotor to complete one rotation with reference to that location.

D. Convergence at the Rotor Center

Rotor convergence is defined as the condition where the catheter is at the center of the rotor. An interesting observation on RPR, based on previous studies, is that it increases to 1 as the catheter is advanced towards the rotor center from an initial location away from the center [10]. Therefore, using this relationship, the following RPR value can be used as the mathematical condition for rotor convergence.

$$\mathrm{RPR} \to 1 \Rightarrow \tau \simeq 1 \qquad (1)$$

E. Proposed Catheter-guidance Algorithm

1) Overview—A block diagram illustrating the algorithm's input and output is provided in Fig. 2. The primary input to the algorithm is the coordinates of the discretized $2D$ search space that was discussed earlier. In order to process the probability estimates, the algorithm utilizes the FAB (Φ) and RPR (τ), hence making them the other pair of the input parameters.

The output of the algorithm is the $2D$ coordinates of the estimated location of the rotor center. Briefly, the entire search process using the algorithm works as follows: the catheter is initially placed at any arbitrary location on the tissue, where bipolar EGMs are recorded and subsequently, FAB and RPR are computed. Now, rotor convergence is investigated and if rotor convergence is not achieved, the inputs are provided to the algorithm for further analysis. This completes one iteration of the algorithm. The catheter is now moved to the location estimated by the algorithm, and the process of EGM recording, characteristics

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computation and rotor convergence verification are repeated for this new location. This search procedure continues until the algorithm locates a rotor, or until it reaches a maximum number of iterations.

2) Mathematical Formulation—Consider a $2D$ $N \times N$ search grid, where each location is given by $S_n = (x_n, y_n)$, $n \in \{1, 2, 3, \ldots, N\}$. The center of the catheter can be placed anywhere in S_n. Then, the $2D$ coordinates of the FAB, Φ, are determined and are given by S_Φ. Let R be a random variable representing the rotor's presence in the search grid. Hence, $P(R = S_n)$ is the probability of rotor convergence at location S_n.

As shown in Fig. 1, with the center of the catheter as the origin (location A in the figure), the vector from this center to S_Φ and its normal vector are defined as the new coordinate system (x^*, y^*). Then, for every S_n, the angle θ_n and distance (*i.e.* magnitude of the vector) d_n are calculated with respect to the new coordinate system. The algorithm now represents every location S_n in polar form as $d_n e^{j\theta_n}$. Fig. 1 shows two example locations (see squares labeled as S_n) and their corresponding parameters. For example, for location with $\overrightarrow{AC}$, $\theta_n = 0$ and $d_n = d_{max}$, where d_{max} is the maximum distance from A.

The Bayesian formulation of the algorithm is described below:

$$P(R = S_n \mid \Phi, \tau) = \frac{P(R = S_n)P(\Phi, \tau \mid R)}{P(\Phi, \tau)} \quad (2)$$

where,

$$P(\Phi, \tau) \triangleq \sum_{n=1}^{N} P(R = S_n)P(\Phi, \tau \mid R)$$

In Eqn. 2, $P(R = S_n/\Phi, \tau)$ is the posterior probability distribution over the search grid, which indicates the probability of rotor convergence at every S_n given the observed EGM characteristics (*i.e.*, Φ and τ); $P(R = S_n)$ is the prior probability distribution; $P(\Phi, \tau/R)$ is the likelihood function of the EGM characteristics and $P(\Phi, \tau)$ is the normalization function for the probability distribution $P(R)$. The rest of this section describes how we employed the physical characteristics of an AF rotor source to develop the likelihood distribution in Eqn. 2.

The initial prior is considered to be a uniform distribution, implying that every location in the search grid initially has equal probability for the rotor to be present. The likelihood function is designed as the sum of two likelihoods – one function for Φ and the other for τ. Hence, the total likelihood function is defined as follows:

$$P(\Phi, \tau \mid R) \triangleq L_\Phi(\theta) + L_\tau(d) \quad (3)$$

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where, $L_\Phi(\theta)$ and $L_\tau(d)$ are the likelihood distribution functions corresponding to Φ and τ, respectively; θ refers to the set of unique angles (in radians) that are calculated as discussed earlier; and similarly d is the set of unique distances.

The distribution for $L_\Phi(\theta)$ is designed to be linear, based on the observations from our previous studies [10]. An example of this distribution is illustrated in Fig. 3. $L_{\Phi min}$ and $L_{\Phi max}$ are the minimum and maximum likelihood values that are hard-coded in the algorithm. θ_{th}^{+} and θ_{th}^{-} are the threshold values within the direction of the FAB (*i.e.*, $\theta = 0$), which indicate that the likelihood is always maximum.

The distribution for $L_\tau(d)$ is a multivariate distribution as shown in Fig. 4. To construct $L_\tau(d)$, we begin by assuming a linear model for the two parameters τ and d. The range for τ is hard-coded to be between the constants τ_{min} and τ_{max}, which are empirical values based on extrema of the linear region of the function $\tau(d)$. The values of d range from 0 to the maximum distance with respect to the current location of recording (d_{max}, as shown in Fig. 1). Then, if the RPR computed at the current location of recording is τ_0, the corresponding distance value d_0 is estimated by minimizing the residual error with respect to the linear model. The maximum likelihood $L_{\tau max}$ for the value τ_0 is then assigned to the distance value d_0. This creates the likelihood distribution for a particular τ over the distance values d. Hence, the likelihood for increasing values of τ *vs.* d results in a multivariate distribution, as illustrated in Fig. 4.

From Fig. 4, it can be seen that, for τ_{min}, the maximum likelihood lies at the farthest distance; it then gets shifted towards the shorter distances gradually with increasing τ, and finally for τ_{max} it lies at the shortest distance available with respect to the current location of recording (which is 0). The proposed likelihood distribution ensures that for low RPR values, the farther search grids to the catheter center have higher probabilities of rotor convergence, while for the higher RPR values, the closer search grids have higher probability. This design is motivated by our prior work [10].

The overall likelihood is then calculated using Eqn. 3. This is then multiplied with the uniform prior in the first iteration and normalized to produce the posterior probability distribution $P(R = S_n/\Phi, \tau)$. From the second iteration of the algorithm, the prior is replaced by the posterior obtained from previous iteration and this process is repeated during every iteration. The algorithm reports the location of the highest posterior probability (S_R) as the output, then moves the catheter to this new estimated location and repeats the entire process until a rotor is located or the algorithm reaches to a maximum number of iterations.

III. Results

The algorithm started by placing the Lasso catheter at an initial location on the $2D$ atrial tissue. It then guided the catheter iteratively based on the EGM characteristics and the procedure described in Section II. The constant parameters in the algorithm $\theta_{th} = 0.056\pi$, $\tau_{min} = 0.2$ and $\tau_{max} = 0.5$ were determined empirically. The process was repeated until a rotor was located or a maximum number of iterations of 20 was reached. The algorithm was executed for a total of 114,921 uniformly spaced initial catheter positions, and the ratio of

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the number of successful rotor localizations compared to the number of trials was reported as the convergence rate.

Without any catheter-guidance algorithm, the existing clinical strategy to search for a rotor consists of randomly placing a catheter in the atrium until the source is localized or the clinician gives-up after several placements. We implemented this strategy and applied it to our AF computer simulated data for comparing it with our proposed catheter-guidance algorithm. The random placement strategy follows the same initial placement and rotor-convergence conditions as the ones explained in Section II.

Fig. 5 shows the catheter's path starting from four initial locations. The voltage map of the rotor can be seen in the background. Each path consists of 3 steps of catheter placement starting from s_1, followed by s_2 and s_3. In the third step, s_3, the catheter guidance was stopped because the rotor-convergence condition was met, implying that the rotor center was encompassed by the catheter. The algorithm was executed during steps s_1 and s_2 of each path. As can be seen in this figure, when the catheter was farther from the center of the rotor, the algorithm made the catheter take larger jumps (*i.e.*, s_1 to s_2), but as it got closer to the rotor-center, the algorithm tended to take shorter jumps.

Table I shows the percentage of trials in which the algorithm successfully located a rotor source. As can be seen from this table, the proposed method was able to locate the rotor source in all the 114,921 cases with a 100% convergence rate, while the random-placement strategy was successful in only 34% of the cases.

Table I also reports the average number of steps taken until (and including) rotor convergence. As shown in the table, the mean±std over the entire grid was 3.37 ± 1.05 steps, and the median was 3 steps. The mean±std was 6.58 ± 3.72 for the random catheter-placement strategy, considering only the convergent scenarios. These results clearly demonstrate the robustness of the proposed algorithm to successfully locate an AF rotor source within a few iterations and independent of how far or close the starting location is.

IV. Conclusion

We developed a novel catheter-guidance algorithm to localize rotors outside the pulmonary veins in the atria. The algorithm was designed using a Bayesian method to iteratively guide a Lasso catheter to the rotor center from any arbitrary location on the tissue. We evaluated the proposed algorithm using simulated human AF data and compared it to a random catheter-placement method inspired by the existing clinical strategy. Our evaluation demonstrated that the algorithm's performance is stable, regardless of the distance or direction of the starting location from the rotor center. Hence, with improvements to the algorithm in the future (such as incorporating $3D$ atrial geometry, introducing multiple rotors and heterogeneity, etc.), a full-fledged software package using the algorithm could be developed and potentially integrated into clinical EP systems to locate rotors in real time during an ablation procedure.

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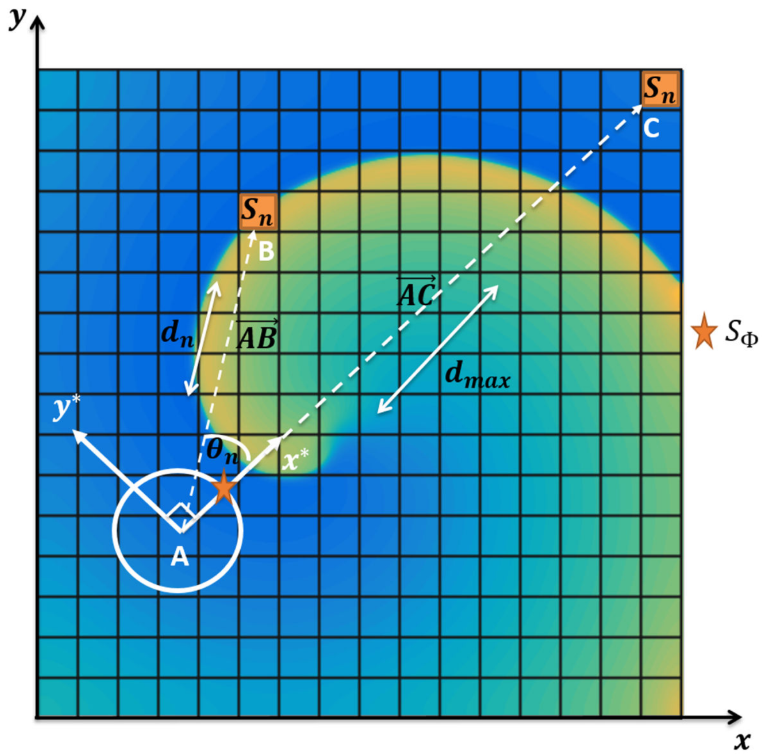

Fig. 1.

Discrete 2D search grid and algorithm parameters – The voltage map of the rotor is shown in the background. The circle is a Lasso catheter and A is its center, the squares labeled as S_n are two example grid locations, and the star indicates the FAB.

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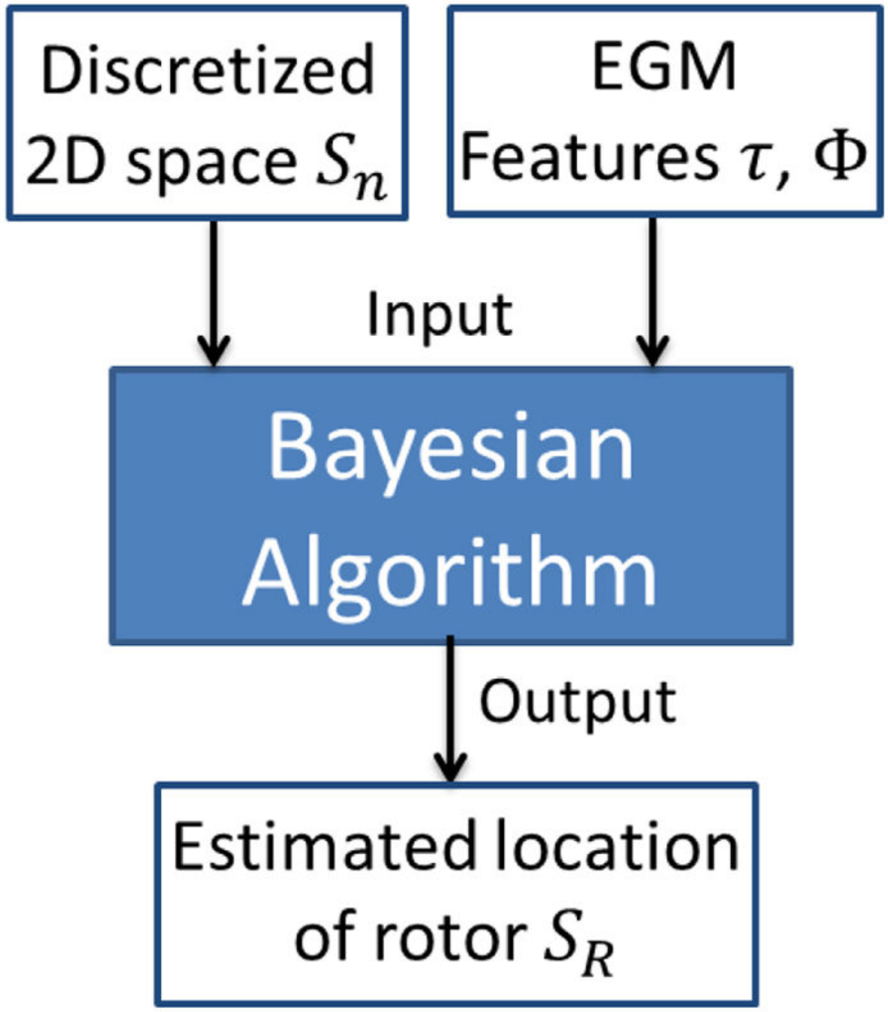

Fig. 2.

Overview of the guidance algorithm – The inputs are the search space and the two EGM characteristics, RPR (τ) and FAB (Φ) and the output is the estimated location of rotor.

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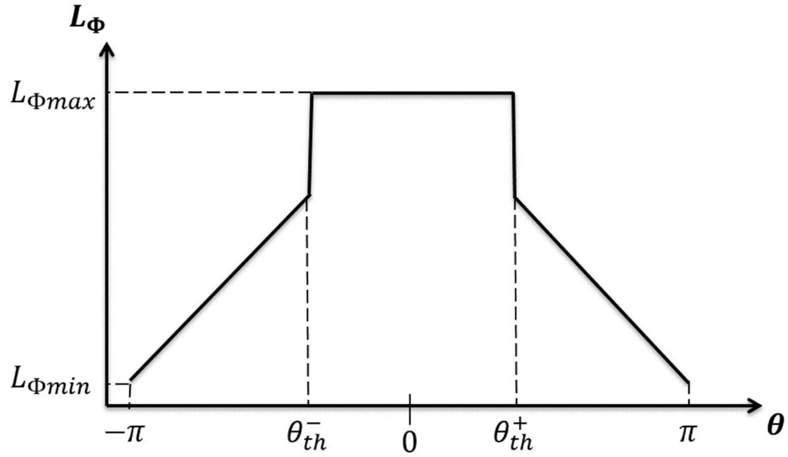

Fig. 3.

Likelihood distribution corresponding to the function $L_\Phi(\theta)$ – $L_{\Phi min}$ and $L_{\Phi max}$ are the minimum and maximum likelihood values selected to be 0.1 and 2, respectively. θ_{th}^+ and θ_{th}^- are -0.056π and 0.056π, respectively.

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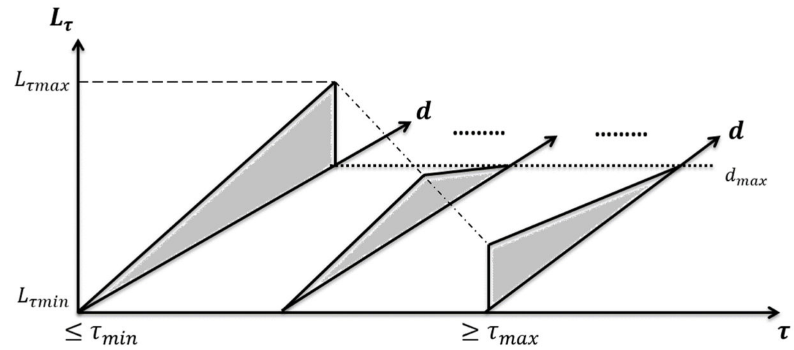

Fig. 4.

Likelihood distribution corresponding to the function $L_\tau(d)$ – $L_{\tau max}$ and $L_{\tau min}$ are maximum and minimum likelihood values and are selected to be 0 and 1, respectively. d_{max} is the maximum distance with respect to the current catheter location.

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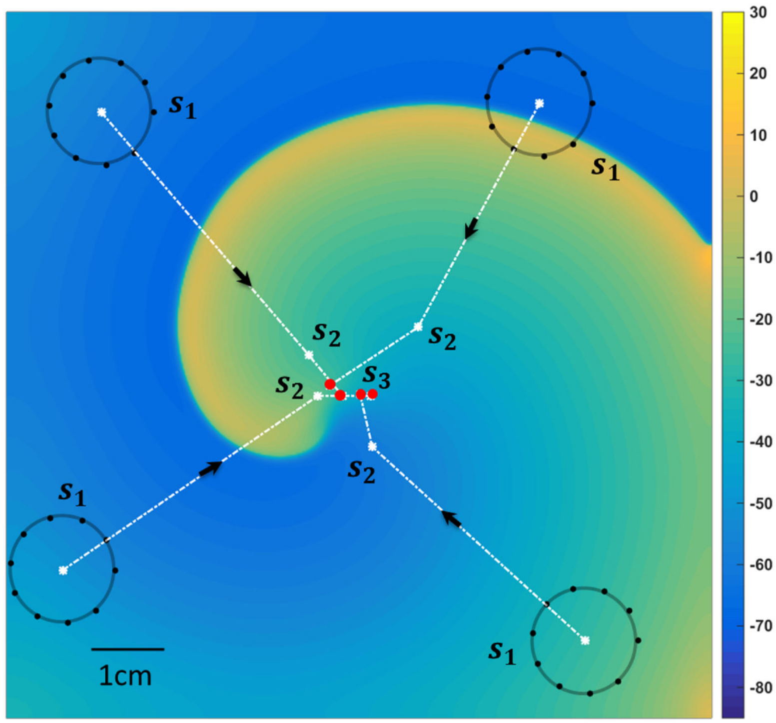

Fig. 5.
Some examples of the catheter-guidance paths using the proposed algorithm – Each path is indicated from the first step, s_1, to the rotorconvergence location in s_3.

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TABLE I

Results of Rotor localization algorithm

Method	Convergence Rate (%)	Number of steps to convergence (mean ± std)
Proposed Algorithm	100	3.37 ± 1.05
Random catheter placement	34	6.58 ± 3.72