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A Novel Catheter-Guidance Algorithm for Localization of Atrial Fibrillation Rotor and Focal Sources

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Abstract

Locating atrial fibrillation (AF) focal and rotor sources can help improve target ablation therapy for AF. However, it remains unclear how to use the information provided by multi-polar diagnostic catheters (MPDC) to locate AF sources. Our aim was to develop a catheter-guidance algorithm to locate AF focal and rotor sources using a conventional MPDC. We simulated a 10 cm x 10 cm atrial tissue with focal and rotor sources using the Nygren *et al.* ionic model. We modeled a Lasso MPDC with 20-unipole electrodes placed with a spacing of 4.5-1-4.5 mm (diameter, d=15 mm) along a circle to obtain 10-bipole electrograms. Starting from an initial location, the algorithm, which was blinded to the location and type of the AF source, iteratively advanced the MPDC by moving its center to the location of the first activated bipole (FAB). The algorithm located an AF source if a stopping condition for either source was satisfied using bipole electrogram characteristics extracted from the MPDC placement. We tested the algorithm for a single rotor and focal source for all possible initial positions on the simulated tissue and repeated it for a random placement with a maximum of 20 possible placements at every trial. The algorithm located the AF source for 100% of trials and on average required 5.99 ± 1.92 placements to an AF source. This algorithm may be used to iteratively direct an MPDC towards an AF source and allow the AF source to be localized for customized AF ablation.

Keywords

atrial fibrillation; patient-specific AF ablation; rotor and focal source; multi-polar diagnostic catheter

I. Introduction

Atrial fibrillation (AF) is the most common arrhythmia among cardiovascular disease with more than 2.3 million people affected annually in the United States and a leading cause of stroke and heart failure [1]. The most common and effective treatment of AF is with

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pulmonary vein isolation (PVI) via catheter ablation; however, this method has only a 40–60% long-term success rate [2], which is hypothesized to be caused by the presence of additional AF sources inside the atria [3]. To increase the effectiveness of PVI, it is necessary to locate those additional sources and guide a customized ablation accordingly.

Currently, the most common means of localizing AF sources is by mapping the entire atrium with a basket catheter and generating a phase, causality, or conduction velocity (CV) map [4], [5]. However, using basket catheters adds additional cost and risk to the patient. In this paper, we develop a novel algorithm to locate AF sources using electrogram characteristics gathered from a conventional multipolar diagnostic catheter (MPDC) as an add-on algorithm to the existing clinical software without using basket catheters. The proposed algorithm is able to guide a conventional MPDC to localize rotor or focal AF sources, without the need to map the entire atrium. The proposed algorithm uses the electrogram characteristics from MPDC electrograms at any placement of the catheter to iteratively guide a Lasso MPDC towards the AF source, and identify whether the target is a rotor or focal source. This is the first work to localize any type of AF source without a prior assumption on the AF source being a rotor or focal.

This paper is organized as follows. Section II describes the proposed MPDC characterization method as well as the catheter-guidance algorithm. Section III reports the results of the proposed catheter-guidance algorithm. The paper is concluded in Section IV.

II. Methods

A. Human Atrial Model and Simulation of MPDC Electrograms

The proposed algorithm was tested on a 10 cm x 10 cm simulated 2D tissue sample with spatial resolution of 0.025 cm and a sampling frequency of 500 Hz using the Nygren *et al.* human atrial cell model [6]. The MPDC was simulated using a replica of a 20-unipole (10-bipole) Lasso catheter (Biosense Webster, Diamond Bar, CA) with 15 mm diameter and 4.5-1-4.5 mm electrode spacing (see Fig. 1A and B). The unipole electrogram for a specific tissue sample location is calculated by Eqn. (1):

$$\phi_e(x_r, y_r) = \sum_{k=1}^K \frac{\Delta v_{m_k}}{\sqrt{(x_k - x_r)^2 + (y_k - y_r)^2}} \quad (1)$$

where K represents the total number of sample points on the tissue, ∇^2 represents the Laplacian operator, v_{m_k} represents the simulated transmembrane potential at the k^{th} atrial cell, (x_k, y_k) represents the coordinates of the k^{th} atrial cell, and (x_r, y_r) represents the coordinates of the recording site. Bipole electrograms are calculated as the difference between MPDC unipole electrogram pairs. Fig. 1A and B show an example of bipole electrode locations and the corresponding bipole electrograms are shown in Fig. 1C.

B. Cycle Detection

Once an MPDC is placed and bipole electrograms are obtained, the local activations are identified and sorted into cycles. Local activations are identified from bipole electrogram data at maximum negative deflections that are greater than a threshold ($Th = 0.5$ mV) [7] with a refractory period (RP) of 50 ms [8]. Any local activations that occur within the refractory period of another activation are ignored. All recorded local activations have their activation times stored for further analysis.

The local activations are then sorted into cycles using a search window method as described next. Starting with the electrogram with the most recorded activations (ref_egm), delays from the reference activation and the next electrogram local activations are compared to a search window (τ). The local activation resulting in the smallest delay in range of τ is stored into the current cycle. In the event that no activations are found within τ , a “miss” is recorded in the cycle data. Algorithms 1 and 2 summarize the local activation and cycle detection algorithms, and Fig. 1C shows an example of where two cycles were successfully identified.

C. MPDC Electrogram Characterization

Once all the cycles are sorted from MPDC bipole electrograms using Algorithm 2, the following five characteristics are extracted for every cycle, n :

First Activated Bipole (FAB)—The FAB is determined as the bipole having the earliest local activation [9], as shown in Fig. 1 and described by Eqn. (2):

$$FAB_n = \arg \min_i \{AT_{i,n}\}_{n=1:N}^{i=1:10} \quad (2)$$

where AT is the cycle sorted activation data obtained by using Algorithm 2, i represents the current bipole, n represents the current cycle, and N represents the total number of cycles.

Algorithm 1

Local Activation Detection

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- 1: **Input:** Electrogram Data (bipole/unipole), Refractory Period ($RP = 50$ ms), and Negative Deflection Threshold ($Th = 0.5$ mV)
 - 2: **for** $i = 1:10$ **do**
 - 3: $egm \leftarrow$ get electrogram data for current bipole/unipole
 - 4: $degmdx \leftarrow$ calculate maximum negative deflection on egm
 - 5: $raw_AT \leftarrow$ store egm times where $degmdx > Th$
 - 6: **for** $n = 1:\text{length}(raw_AT) - 1$ **do**
 - 7: $RPcheck = raw_AT_{n+1} - raw_AT_n$
 - 8: **if** $RPcheck > RP$ **then**
 - 9: $valid_AT_{i,n} = raw_AT_n$
 - 10: **end if**
-

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11:   end for
12:    $DAT_n := valid\_AT$ 
13: end for
14: Output: Detected Activation Times ( $DAT$ )

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Algorithm 2

Cycle Detection

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1: Input: Detected Activation Times ( $DAT$ ), Search Window ( $\tau$ )
2:  $ref\_egm \leftarrow$  The number of the bipole with the maximum number of activations
3:  $N \leftarrow$  Number activations in  $ref\_egm$  (number of cycles)
4: for  $j = 1 : N$  do
5:    $RA \leftarrow$  set reference activation as  $DAT_{ref\_egm,j}$ 
6:    $pointer = ref\_egm + 1$  OR  $1$  if  $ref\_egm = 10$ 
7:    $AT_{ref\_egm,j} \leftarrow RA$ 
8:   for  $i = 1 : 9$  do
9:      $delays = |RA - DAT_{pointer,i}|$ 
10:     $inRange \leftarrow$  find activations in range ( $delays - \tau$ )
11:    if  $length(inRange) \neq 1$  then
12:       $RA \leftarrow$  update with closest activation in range
13:       $AT_{pointer,j} = RA$ 
14:    else
15:       $AT_{pointer,j} = []$ 
16:    end if
17:     $pointer = ref\_egm + 1$  OR  $1$  if  $ref\_egm = 10$ 
18:  end for
19: end for
20: Output: Cycle Sorted Activation Data ( $AT$ )

```

Total Conduction Delay (TCD)—The total conduction delay for a given cycle is the sum of individual conduction delays between neighboring bipoles [9], as shown in Fig. 1B and C as described by Eqns. (3)–(4):

$$CD_{i,n} = \begin{cases} |AT_{i,n} - AT_{i+1,n}|, & \text{if } i \leq 9 \\ |AT_{10,n} - AT_{1,n}|, & \text{o.w.} \end{cases} \quad (3)$$

$$TCD_n = \sum_{i=1}^{10} CD_{i,n} \quad (4)$$

Cycle Length (CL)—The cycle length of every bipole is determined as the time delay between successive activations during two consecutive cycles [9], as shown in Fig. 1C and described by Eqn. (5).

$$CL_n = \frac{1}{10} \sum_{i=1}^{10} |AT_{i,n} - AT_{i,n+1}| \quad (5)$$

Cycle Width (CW)—Cycle width for each cycle is calculated as the time delay between the FAB and last activated bipole (LAB), as shown in Fig. 1C and described by Eqns. (6)–(7).

$$LAB_n = \arg \max_i \{AT_{i,n}\} \quad (6)$$

$$CW_n = AT_{LAB_n,n} - AT_{FAB_n,n} \quad (7)$$

Suspected Activated Bipoles—A suspected activated bipole (SAB) is a bipole that is located on a rotor center, resulting in a low-magnitude local activations. SABs are identified from the bipole electrogram data with “missed” local activations in the cycle data and are distinguished from perpendicular colliding wavefronts by confirming whether the corresponding unipolar electrogram local activations are less than threshold, Th . This must be done because a perpendicular collision has low-magnitude bipole activations with distinct unipole activations, while a SAB must have both low-magnitude unipole and bipole activations.

D. Proposed Catheter-guidance Algorithm

Guidance Strategy—At any MPDC location, the electrograms are recorded and cycles are detected. For every cycle, the algorithm calculates FAB, TCD, CL, CW, and SAB. The algorithm then selects the first two cycles with a consistent FAB and calculates the average TCD, CL, and CW. The algorithm then moves the center of the MPDC to the location of the FAB (or SAB if there are any) and repeats this process until an AF source is found or a maximum number of MPDC placements is reached. An AF source is identified using two independent stopping conditions depending on whether the MPDC is near a rotor or a focal source. A rotor source is identified if $TCD/CL < 0.9$. This condition assures that the MPDC is encompassing a rotor [10]. A focal source is localized if $CW < d/CV$, which means that a focal source is located inside the MPDC, as the time that the wavefront takes to propagate to the outside of the MPDC is less than the time that it takes to pass through it. Algorithm 3 details the process of the proposed catheter-guidance algorithm, and the steps are shown in Fig. 2.

E. Random Placement Strategy

The existing clinical strategy to search for an AF source includes the random placement of an MPDC in different locations in the atrium until the source is localized. We implemented this strategy and applied it to our AF simulated data for comparison purposes with the proposed catheter-guidance algorithm. The random placement strategy follows the same initial placement and stopping criteria as the ones explained for the proposed guidance algorithm; however, the following placements of the MPDC are decided randomly.

Algorithm 3

MPDC Guidance Strategy

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1: Input: Initial MPDC center location  $(x_i, y_i)$ , MPDC diameter  $(d)$ , Approximate tissue conduction velocity  $(CV)$ ,
   Maximum number of MPDC placements  $(maxit)$ 
2: Place MPDC at  $(x_i, y_i)$ 
3: Initialize no AF source found  $(AFT = 0)$ 
4: Initialize Number of MPDC Placements  $(P = 1)$ 
5: while  $AFT = 0$  AND  $P \leq maxit$  do
6:   Gather 20 unipolar electrograms at current MPDC location using Eqn. (1)
7:    $egm \leftarrow$  Compute bipolar electrogram data
8:    $DAT \leftarrow$  Apply Algorithm 1 with  $egm$ 
9:    $AT \leftarrow$  Apply Algorithm 2 with  $DAT$ 
10:  Compute MPDC Characteristics using Eqns. (2)–(7)
11:  Determine if any SAB exists with unipole and bipole  $AT$  ( $SAB = 1$ )
12:  if  $TCD/CL \geq 0.9$  then
13:     $AFT \leftarrow 1$ : Rotor Found
14:    if  $SAB = 1$  then
15:      Move MPDC to SAB location
16:      Repeat Lines 6–10
17:    if  $TCD/CL \geq 0.9$  then
18:      Keep MPDC on SAB location
19:    else
20:      Move MPDC back to original stopping location
21:    end if
22:  end if
23:  else if  $CW \geq d/CV$  then
24:     $AFT \leftarrow 2$ : Focal Found
25:  else
26:    Place MPDC at FAB location
27:     $P \leftarrow P + 1$ 
28:  end if
29: end while
30: Output: Number of MPDC Placements  $(P)$ , Source Type  $(AFT)$ 

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III. Results and Discussion

The proposed catheter-guidance algorithm was used to locate a rotor and focal source as described in Table I. The algorithm started from an initial position of the MPDC on the simulated atrial tissue and guided the catheter until an AF source was identified or a maximum number of 20 iterations (*maxit*) was reached. The algorithm was considered successful if it was able to correctly identify the AF source before the maximum number of placements was reached. For cycle detection (Algorithm 2), we set $\tau = 100$ ms. For the focal stopping condition, we assumed $CV = 75$ cm/s [11]. We report the success rate, average number of MPDC placements that the algorithm takes before it locates an AF source, and average distance of the stopping point to the true AF source location (average localization distance). The same process was repeated for the random placement strategy. All results are reported in Table I and a few examples of the catheter-guidance algorithm can be seen in Fig. 3.

The catheter-guidance algorithm was able to successfully locate and identify both types of AF sources from all possible initial locations and significantly outperformed the random placement strategy in successfully localizing either AF source (with $p < 0.0001$). It was observed that the number of MPDC placements is comparable between the catheter-guidance algorithm and the random placement strategy for both rotor and focal sources (6.02 vs. 6.74); however, this is due to excluding all unsuccessful trials from the random placement strategy. It was also observed that the catheter-guidance algorithm outperformed the random placement strategy in the average source localization distance (2.4 vs. 5.2 mm), which indicates the effectiveness of the proposed catheter-guidance strategy. It is also worth mentioning that the average localization distance was significantly less than the radius of the MPDC (7.5 mm) regardless of source type. To further increase localization accuracy the rotor/focal stopping conditions may be adjusted to become more/less stringent. In addition, the guidance analysis was performed over two cycles of the electrogram data at every MPDC placement, so the algorithm took about 3.5 seconds on average to locate a rotor source with CL of 272 ms and about 7.7 seconds to guide the MPDC from the corner locations to the center of the rotor.

IV. Conclusions

The proposed algorithm was assessed using simulated human atrial model data and compared against an unguided (i.e., random) MPDC placement strategy, which was inspired by existing clinical ablation procedure. Our results were promising as the algorithm guided an MPDC with 100% localization success and localization distance of < 7.5 mm. Such an algorithm could play a significant role in the successful detection and ablation of AF sources outside the PVs and in increasing the success of AF elimination procedures. As a result, both the safety and outcomes of the ablation procedures could be improved considerably for the millions of patients afflicted by this debilitating disorder.

Acknowledgments

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References

1. Go A, et al. Aha statistical update. *Circulation*. 2013; 127:e62–e245.
2. Weerasooriya R, et al. Catheter ablation for atrial fibrillation: are results maintained at 5 years of follow-up? *JACC*. 2011; 57(2):160–166. [PubMed: 21211687]
3. Theis C, et al. Arrhythmia termination versus elimination of dormant pulmonary vein conduction as a procedural end point of catheter ablation for paroxysmal atrial fibrillation a prospective randomized trial. *Circ Arrhythm Electrophysiol*. 2015; 8:1080–1087. [PubMed: 26297786]
4. Narayan S, et al. Clinical mapping approach to diagnose electrical rotors and focal impulse sources for human atrial fibrillation. *JCE*. 2012; 23(5):447–454.
5. Rodrigo, M., et al. Atrial sources identification by causality analysis during atrial fibrillation. EMBC, 2015 37th Annual International Conference of the IEEE; IEEE; 2015. p. 3783-3786.
6. Nygren A, et al. Mathematical model of an adult human atrial cell the role of k⁺ currents in repolarization. *Circ Res*. 1998; 82(1):63–81. [PubMed: 9440706]
7. Paul T, et al. Epicardial mapping: how to measure local activation? *PACE*. 1990; 13(3):285–292. [PubMed: 1690401]
8. Jaïs P, et al. Mapping and ablation of left atrial flutters. *Circulation*. 2000; 101(25):2928–2934. [PubMed: 10869265]
9. Ganesan P, et al. Characterization of electrograms from multipolar diagnostic catheters during atrial fibrillation. 2015:1830–1838.
10. Ghoraani B, et al. Localized rotational activation in the left atrium during human atrial fibrillation: Relationship to complex fractionated atrial electrograms and low-voltage zones. *Heart Rhythm*. 2013; 10(12):1830–1838. [PubMed: 24016695]
11. Hansson A, et al. Right atrial free wall conduction velocity and degree of anisotropy in patients with stable sinus rhythm studied during open heart surgery. *Eur Heart J*. 1998; 19(2):293–300. [PubMed: 9519324]

Fig. 1. (A) Rotor wave with the MPDC on the tissue. (B) A close up of the MPDC with the numbered bipole electrodes. (C) The electrograms at the MPDC location. The numbers indicate the lead number of the bipole electrodes.

Fig. 2.
The flow diagram for the proposed catheter-guidance algorithm.

Fig. 3.

Examples of the MPDC being guided to the rotor (A) and focal (B) sources. The lines indicates the guidance path for each MPDC initial location and the dots show the location of the MPDC center throughout each path.

TABLE I

Catheter-guidance Algorithm vs. Random Placement Strategy

AF Source Type	Success Rate	Average Number of Placements	Average Localization Distance (mm)
Rotor (CL = 272 ms)	100 (34) *	6.14 ± 1.94 (6.58 ± 3.72)	2.3 ± 1.4 (5.8 ± 2.2)
Focal (CL = 150 ms)	100 (9)	5.83 ± 1.90 (7.37 ± 4.06)	2.6 ± 1.0 (2.7 ± 1.0)

* Random Placement Strategy results shown in parentheses