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Catheter Simulator Software Tool to Generate Electrograms of Any Multi-polar Diagnostic Catheter from 3D Atrial Tissue

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Abstract

Simulations are excellent tools for assessing new therapeutic strategies and are often conducted before implementing new therapy options in a clinical practice. For patients suffering from a heart arrhythmia, the main source of information comes from an intracardiac catheter. One of the common catheters is a Lasso multi-pole diagnostic catheter, which is a catheter that has 20 electrodes in a circular pattern. In this paper, we developed algorithm and simulation software that allows the users to place a multi-pole catheter on the atrial endocardial surface and record electrograms. In 3D atrial tissue, the plane of principal curvature is determined using eigenvectors of catheter vertices, from where the normals are projected and registered to the surface using 3D geodesic distance. This tool provides a platform for performing customized virtual cardiac experiments.

Keywords

Catheter simulation; Cardiac simulation; 3D atrial tissue; Human atrial fibrillation simulation

I. Introduction

Atrial fibrillation (AF) is the most common cardiac arrhythmia, accounting for frequent hospitalizations and increased risks of stroke, heart failure and mortality [1]. Patients with AF are grouped on the basis of the clinical duration and behavior of their AF (i.e., paroxysmal, persistent or permanent), but this does not take into account the mechanisms of their arrhythmia. The mechanisms of initiation and perpetuation of AF in humans are multiple and are still under investigation [2]. Accordingly, there has been a considerable interest in utilizing the atrial electrograms collected from the endocardium for understanding the initiation and sustainability of the AF in the atria [2]. These electrograms are collected during a common AF ablation procedure where a diagnostic multi-polar catheter is inserted into a vein, typically in the groin or neck, and threaded into the left atrium. One of the more commonly used catheters is called a Lasso; it contains 20 electrodes placed in a circular formation.

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Cardiac simulations have been commonly utilized as the first step before clinical trials for any kind of analysis of the electrogram signals from the atrium [3]. For example, if a new strategy for locating AF sources is proposed, then the method can be evaluated on the simulated data before being used in any clinical trials. One such methods is an adaptive catheter-guidance algorithm that can be used to guide a diagnostic catheter towards the AF source in the atria [4]. Implementation and evaluation of such an algorithm on 3D cardiac AF simulated data requires the placement of a diagnostic catheter, such as a Lasso, on the 3D structure of the atrial tissue and recording the corresponding electrograms. Then, the algorithm can analyze the collected electrograms and guide the catheter accordingly until the catheter reaches to the AF source location. However, there is no standard platform for simulating a catheter on a 3D atrial structure and recording the electrogram signals. Although 3D cardiac simulations have been performed and multipolar diagnostic catheters are commonly used in clinical practice, there is no platform dedicated to the simulation of a Lasso catheter on the 3D structure of the heart with the purpose of collecting electrogram signals. In this paper, we developed a platform to simulate a Lasso multipolar catheter anywhere of the endocardium in the atria and collected the corresponding electrograms.

The organization of this paper is as follows: Section II describes the generation of the 3D human AF simulation data, the simulation electrogram signals, and our proposed catheter simulator algorithm. In Section III, the results of the algorithm are presented, and the paper is concluded in Section IV.

II. Method

A. Human Atrial Fibrillation Simulation

A human atrial model was used to simulate AF in a fully 3D realistic atrial anatomy with spatial resolution of 0.025cm [5]. A stable source of AF source with cycle length of 270ms was simulated using the Nygren *et al.* [6] human atrial model, which was based on average voltage-clamp data recorded from the isolated single myocytes from typical bulk atrial tissue. The generated transmembrane potentials were collected with a sampling frequency of 500Hz.

B. Lasso Multipolar Diagnostic Catheter

Figure 1 shows the structure of a 20-electrode Lasso catheter (Biosense Webster, Diamond Bar, CA) with a 15mm diameter and 4.5-1-4.5mm electrode spacing. These electrodes are specifically located so that 10 are placed evenly around the circular catheter, while the other ten have a slight offset (i.e., 1mm) along the circular pattern. Each electrode is also known as a unipole, and the ten locations directly in between offset electrode pairs are known as bipoles. Each bipole is indicated by a pair of unipoles on the Lasso catheter.

C. Electrogram Simulation

Once a Lasso catheter is placed on the atrial tissue, each electrode collects an electrogram recording, which is referred to as a unipole electrogram. The difference between the unipole electrograms of a unipole pair is denoted as the bipole electrogram of the corresponding bipole. Unipole electrograms for each electrode location are simulated using the equation for

dipole source density of the transmembrane potential assuming an infinite volume conductor:

$$E_{Uu} = \sum_{i=1}^M \frac{D \nabla(V_{mi}) \cdot \vec{r}_i}{|\vec{r}_i|^3} \quad (1)$$

where, E_{Uu} is the unipolar electrogram simulated at the 3D location of u , D is the diffusion coefficient which was set as $0.001 \text{ cm}^2/\text{s}$, V_{mi} is the transmembrane potential at i^{th} location, ∇ is the gradient operator, $\vec{r}_i$ is the vector from the 3D location of u to i^{th} location, and M is the number of sample space in the atria. After simulating all the electrograms for all the unipole locations on a Lasso catheter, the bipolar electrograms are then simulated as follows:

$$E_{Bb} = E_{Ub1} - E_{Ub2} \quad (2)$$

where $\{E_{Bb}\}_{b=1:10}$ indicates the 10 bipolar electrograms at a catheter placement.

B. Proposed Catheter Placement Method

The process of the developed Lasso catheter placement algorithm is displayed in Figure 2. The input to this algorithm is the coordinate of the point on the 3D atrium where the Lasso catheter will be placed. The algorithm projects the Lasso template on the 3D structure of the atrium through steps 2 to 5 and returns the coordinates of the unipoles and bipoles on the atrium along with their corresponding unipolar and bipolar electrograms. Figure 3 illustrates each step of the process on the 3D structure of the left atrium.

Step 1. Placement of The Center of Catheter—The 3D surface of the atrium is introduced as a matrix, $\mathcal{S}$, shown in Eq. (3). This is used to identify coordinates of locations where the catheter may be simulated. M is the total number of points in the 3D atrial space.

$$\{S_i\}_{i=1:M} = \{(x_i, y_i, z_i)\}_{i=1:M} \quad (3)$$

Another 3D matrix, $\{V_i\}_{i=1:M}$, is introduced for the transmembrane potentials of each point in the atrial space, $\mathcal{S}$. For every catheter placement, the center point location of the catheter is denoted as C_c as follows:

$$C_c = (x_c, y_c, z_c) \quad (4)$$

Step 2. Gather Surface Points R Distance Away—Next, the algorithm identifies all the surface points in the atrial space, $\mathcal{S}$, that are a distance R away from the center of the catheter. R is the radius of the Lasso catheter. To perform this process, we use the Euclidean distance between two points A and B as shown below:

$$D_E(A, B) = \sqrt{(A_x - B_x)^2 + (A_y - B_y)^2 + (A_z - B_z)^2} \quad (5)$$

and use the following equation to find all the points S_j that are within a tolerance (Tol) of the center of the catheter, C_c :

$$R_P = \left\{ (x_j, y_j, z_j) \mid \left| D_E(C_c, S_j) - R \right| \leq Tol \right\}_{j=1:N} \quad (6)$$

In this work, we set the value of Tol to 1 sample (i.e., 0.025cm) and denoted the set of all the points within a distance of R as R_P . However, the R_P points are selected based on the Euclidean distance so it is possible that some of those points are farther in their surface distance. This scenario is common for the catheter placements that are close to the pulmonary veins, where the Euclidean distance to a different vein can be less than the distance along the surface. In those cases, we may have some of the selected R_P points on the anterior side, while some may be on the posterior. To avoid such problems, the algorithm checks for the geodesic distance of all the R_P points to ensure that they are within an acceptable geodesic distance from the catheter center. In this work, we use the algorithm in [7] to calculate the geodesic distance between any R_P points and the center of the catheter, C_c ; we denoted the geodesic distance as $D_G(R_{Pk}, C_c)$. The algorithm then selects only the points that are within a tolerance, Th , of 0.15 cm away from the catheter center. This new set of selected points is denoted as R_S and described in Eq. (7).

$$R_S = \left\{ (x_k, y_k, z_k) \mid \left| D_G(R_{Pk}, C_c) - R \right| \leq Th \right\}_{k=1:K} \quad (7)$$

The Euclidean distance at the beginning is used to select the R_P points in order to decrease the number of geodesic distance computations, which is more expensive to compute than the Euclidean distance.

Step 3. Calculate Normal From The Surface Points—The K selected points from the previous step, R_S , are then used to calculate a normal vector $\vec{n}$ corresponding to the surface ϕ of the points in R_S . First, the algorithm takes the mean of all the input points. This process returns a single location point that is the averaged location of all the R_S points. The averaged point is subtracted from each point in R_S and the resulting points are arranged in a $K \times 3$ matrix. The third eigenvector of this matrix is calculated as the normal vector of the surface representing the points in R_S so the surface perpendicular to this normal vector is identified as surface ϕ .

Step 4. Generate Catheter Template—Next, the template for the electrode locations of the Lasso catheter is calculated on the surface ϕ . The center of the catheter, C_c , is projected on surface ϕ , and then 20 electrodes are created R distance away from the center with each

pair of unipoles separated by 1mm. The following equation describes the catheter template generation process:

$$C_T = \{R * \cos(\theta_e) * \vec{u} + R * \sin(\theta_e) * \vec{v}\}_{e=1:20} \quad (8)$$

where $C_T = \{(x_{Te}, y_{Te}, z_{Te})\}_{e=1:20}$ is the coordinates of the 20 electrodes on the catheter, $\vec{u}$ and $\vec{v}$ are the perpendicular unit vectors at the projected point of the center of the catheter, R is the catheter radius, and θ_i is an the phase angle starting from 0 radians and increasing by 0.13 radians and 0.60 radians for every odd and even numbered electrode, respectively.

Step 5. Electrode Locations—The next step is projecting the generated catheter template on the 3D atrial structure. At each electrode e on surface ϕ , a perpendicular line to the surface is defined as shown in the below equations:

$$L_e = \{C_{Te} + l \vec{n}\}_{l=1:40} \quad (9)$$

where $\vec{n}$ is the normal unit vector at electrode e on surface ϕ , C_{Te} is the coordinates of electrode e on the catheter template, and L_e includes a series of points spaced 0.025 cm apart on the normal line $\vec{n}$ up to 1 cm away from the electrode. The range of l is assigned such that line L_e intersects with the 3D structure of the atria. Figure 4 shows $\{L_e\}_{e=1:20}$ for all the electrodes on the catheter's template.

The minimum Euclidean distance between all the points on the 3D atrial surface and L_e is determined as follows:

$$C_{Ee} = \arg \min_i D_E(S_i, L_e) \quad (10)$$

where S is the 3D atrial structure as defined in Eq. (3), D_E is the Euclidean distance as in Eq. (5), and C_{Ee} is the electrode position on the atrium. However, the atrial structure is 3D and it is possible that the selected electrode is placed on the surface opposite to the center of the catheter. Hence, the algorithm verifies that the electrode position is within an acceptable distance from the center of the catheter before reporting the final electrode location on the atrium. To do so, the algorithm calculates the geodesic distance between the electrode location and the center location of the catheter. If this distance is within 0.125 cm samples tolerance of the radius, R , the electrode location is kept and the method moves to the next electrode location. If the location is not within 0.125 cm, the next 5 minimum surface distances away from the normal line are checked. If none of those locations have a geodesic distance within 0.125 cm, the method increases to the next minimum distance surface distance away until a surface electrode location is determined. The algorithm repeats the process in Eq. (10) until all 20 electrode locations are determined as $\{C_{Ee}\}_{e=1:20}$.

It is worth mentioning that the computation of one geodesic distance takes about 0.3 seconds on average. Hence, the calculation of the Euclidean distance at the beginning helps to decrease the number of the geodesic distance computations that are needed and significantly decreases the computation time in the algorithm. Figure 4 illustrates how the catheter template is projected to the atrial surface along the normal line.

6. Unipole/Bipole Locations—After all 20 electrode locations have been determined, the unipole pairs are labeled as follows:

$$C_{U1} = \{C_{Ee}\}_{e=1:2:19} \quad (11)$$

$$C_{U2} = \{C_{Ee}\}_{e=2:2:20} \quad (12)$$

where $\{C_{U1u}\}_{u=1:10} = \{(x_{U1u}, y_{U1u}, z_{U1u})\}_{u=1:10}$ and $\{C_{U2u}\}_{u=1:10} = \{(x_{U2u}, y_{U2u}, z_{U2u})\}_{u=1:10}$ include the coordinates of the unipole pairs. Next, the bipole coordinates, C_b , are calculated by finding the rounded center point between unipoles one and two as shown in Eq. (13)

$$C_B = \left(\frac{(x_{U1b} + x_{U2b})}{2}, \frac{(y_{U1b} + y_{U2b})}{2}, \frac{(z_{U1b} + z_{U2b})}{2} \right)_{b=1:10} \quad (13)$$

As shown in Figure 1, the bipole locations are only for visual representation. The unipole electrograms are calculated at every unipole location using Eq. (1) and are used to simulate the bipole electrograms at all 10 bipoles. After steps 1 to 6 are performed, the software reports all of the x , y and z coordinates for the bipoles and unipoles on the Lasso catheter ($\{C_{U1}, C_{U2}, C_B\}$), which is placed on the given catheter center, C_C , along with the simulated electrograms ($\{E_{U1}, E_{U2}, E_B\}$). The simulated catheter is then displayed on the 3D atrial surface for visualization and the electrograms are used for analysis. The process is repeated for any new catheter center as needed.

III. Results

The described catheter simulation software platform was implemented in MATLAB and applied to the 3D human AF simulation data. Using the catheter placement method, a 20-electrode Lasso catheter was simulated at a desired location on the atrium. The software was able to successfully place the catheter anywhere on a 3D atrial structure. Figure 5 shows the successful placement of a catheter on the front, roof, and posterior wall of the 3D left atrium.

The catheter simulation method was applied to a 3D simulation during atrial fibrillation, where a stable rotor source on the posterior wall sustains the AF. The simulated catheter placement and the corresponding electrograms are shown in Figure 6. This figure shows a

case where the catheter is placed on the left pulmonary veins (Figure 6A) and a case where the catheter is placed on the rotor (Figure 6B). The unipole electrograms are illustrated as dashed lines and the bipole electrograms are shown as solid lines. The numbers by each electrogram signal indicate the respective bipole on the Lasso catheter. The developed graphical interface for the platform is shown in Figure 7, which can be used to visualize the simulated catheter and electrograms.

IV. Conclusions

The described open-source catheter simulation software tool (source code available upon request) can produce electrograms from user-selected locations for any subset of simulation time. This tool also can be integrated with any cardiac applications that require catheter simulations. One such important application includes the adaptive catheter guidance algorithm to guide a diagnostic catheter towards the AF source in the atria.

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References

1. Matsuo S, Lim KT, Haissaguerre M. Ablation of Chronic Atrial Fibrillation. *Heart Rhythm*. 2007;1461–1463. [PubMed: 17954407]
2. Calkins H, et al. 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. *Heart Rhythm*. 2012; 9:632–696. 11. [PubMed: 22386883]
3. Cherry EM, Evans SJ. Properties of Two Human Atrial Cell Models in Tissue: Restitution, Memory, Propagation, and Reentry. *Journal of Theoretical Biology*. 2008; 254:674–690. [PubMed: 18652834]
4. Ganesan P, Cherry EM, Pertsov AM, Ghoraani B. Characterization of electrograms from multipolar diagnostic catheters during atrial fibrillation. *BMRI*. 2015
5. Harrild DM, Henriquez CS. A computer model of normal conduction in the human atria. *Circ Res*. 2000; 87:e25–e36. [PubMed: 11009627]
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. Soille, P. *Morphological Image Analysis: Principles and Applications*. 2. Secaucus, NJ: 2003. p. 219-221.

Figure 1.
Lasso multipolar diagnostic catheter (Biosense Webster, Diamond Bar, CA) and the electrode, unipole, and bipole arrangement.

Figure 2.
Diagram of the catheter simulation algorithm.

Figure 3.

Catheter placement process on the simulated 3D left atrium substrate. The color on the 3D left atrium represents the simulated transmembrane potential and the numbers match the step numbers in Section II.

Figure 4.
Placement of the catheter template on the 3D atrial surface

Figure 5.

Three examples of successful catheter placement on the front, roof and posterior wall of the 3D atrial surface.

Figure 6.
Simulated Lasso catheter and corresponding electrograms.

Figure 7. Graphical user interface for the simulation of the LASSO catheter electrograms from the LASSO catheter placed on the 3D structure of the left atrium.