Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2014 February 15; 9036: . doi:10.1117/12.2043191.

Toward Standardized Mapping for Left Atrial Analysis and Cardiac Ablation Guidance

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Abstract

In catheter-based cardiac ablation, the pulmonary vein ostia are important landmarks for guiding the ablation procedure, and for this reason, have been the focus of many studies quantifying their size, structure, and variability. Analysis of pulmonary vein structure, however, has been limited by the lack of a standardized reference space for population based studies. Standardized maps are important tools for characterizing anatomic variability across subjects with the goal of separating normal inter-subject variability from abnormal variability associated with disease. In this work, we describe a novel technique for computing flat maps of left atrial anatomy in a standardized space. A flat map of left atrial anatomy is created by casting a single ray through the volume and systematically rotating the camera viewpoint to obtain the entire field of view. The technique is validated by assessing preservation of relative surface areas and distances between the original 3D geometry and the flat map geometry. The proposed methodology is demonstrated on 10 subjects which are subsequently combined to form a probabilistic map of anatomic location for each of the pulmonary vein ostia and the boundary of the left atrial appendage. The probabilistic map demonstrates that the location of the inferior ostia have higher variability than the superior ostia and the variability of the left atrial appendage is similar to the superior pulmonary veins. This technique could also have potential application in mapping electrophysiology data, radio-frequency ablation burns, or treatment planning in cardiac ablation therapy.

1. BACKGROUND

In left atrial fibrillation, a condition in which the atria of the heart beat rapidly and irregularly, it has been shown that irregular electrical activity often originates in the pulmonary veins.¹ In cardiac ablation therapy, the pulmonary veins are electrically isolated from the left atrium by creating radiofrequency lesion lines around the pulmonary vein ostia. For this reason, the pulmonary veins have become the focus of many studies with an emphasis on quantifying their size, structure, and variability.²⁻⁴ Of particular interest is whether pulmonary vein structure is either correlated with disease or could be used in determining treatment strategy. For example, it has been shown that patients with atrial fibrillation are more likely to have variations in their pulmonary vein anatomy as compared with normal controls.^{5,6}

To date, studies of pulmonary vein topology have primarily focussed on classifying pulmonary vein drainage patterns into different categories.^{7,8} Population based studies of pulmonary vein structure have, in part, been limited by the lack of a standardized reference space. Standardized maps are important tools for characterizing anatomic variability across subjects with the goal of separating normal inter-subject variability from abnormal variability associated with disease. In this work, we propose a novel technique for mapping the location of key anatomic structures in the left atrium, namely the pulmonary veins and left atrial appendage into a standardized reference space. We utilize a volumetric ray casting approach to map the original geometry into a flat map geometry by systematically rotating the camera viewpoint to cover the entire field of view. Flat maps of the left atrium have been previously used to visualize electrical activity in the left atrium,⁹ however, in this work we use the flat mapping technique to define a standardized space for left atrial anatomy. The approach is demonstrated on a collection of 10 patient datasets and the results are used to create a probabilistic atlas of left atrial anatomy.

2. METHODS

Standardized Map Computation

The left atrium and pulmonary veins are segmented from a CT dataset using a previously validated semi-automated technique¹⁰ with the result shown at two different views in Figures 1 (a) and (b). Next, each subject is scaled to a standardized volume and registered to a single (atlas) subject using a surface based registration technique.¹¹ In order to create a flat map depicting the pulmonary vein ostia and left atrial appendage, the intersection between the left atrium and each anatomical structure is computed by applying a dilation to the left atrium and finding its overlap with each pulmonary vein and the appendage. A rendering of the extracted pulmonary vein ostia and the appendage boundary is shown in Figure 1(c).

The left atrium is generally considered to be convex (excluding the pulmonary veins and the left atrial appendage). Accordingly, a straightforward ray-tracing approach can be used to drive a flat map of the anatomy. We use the Levoy¹² approach to ray tracing which provides a fast tracing algorithm with inherent smoothing and low aliasing artifacts. The basic rendering equation is $R_{out} = v(t_i) * \alpha(t_i) + R_{in}(1 - \alpha(t_i))$. The rendering equation blends the incoming ray R_{in} with the voxel value, v at each discrete point along the ray using the blending value α . In the case of flat map generation, the rays use an early termination criteria once an ostial voxel is intersected by the ray. The rendered image contains both the assigned value for each pixel (based on the voxel value along the ray) as well as the depth along the ray where the intersection occurred. For the purposes of this work, the assigned value is kept, however, one could use the depth information to refine the alignment of multiple subjects. The forward ray-tracing approach ensures that no holes occur in the final flat map of the ostia because each pixel is individually traced. Additionally, the image normal can be used to provide a regularization on the underlying shape which is generally the result of segmentation on a discrete grid. This is accomplished by weighting $v(t_i)$ using the image normal at the point of intersection. At each point t_i , a vector is calculated by $N(t_i) = \nabla f(t_i) / |\nabla f(t_i)|$ where $\nabla f(t_i)$ is estimated using finite differences. For the purpose of the flat map generation, the lighting source is coincident with the eye, thus negating its effect.

In order to generate a full map of left atrial anatomy, the camera viewpoint is systematically rotated to cover the entire field of view as follows. For each of the 180° rotations in y, the camera viewpoint is rotated 360° about x. At each rotation, a single ray is cast from the camera through the left atrial volume and the value from this ray is stored in the corresponding image location. Parallel ray tracing can be used to reduce distortion. In order to view the interior surface of the left atrium using parallel ray tracing, the volumetric data (and corresponding segmentation volume) are clipped between the camera and left atrium. The flat map computed for the pulmonary vein and appendage ostia in Figure 1(c) is shown in Figure 1(d).

Validation Study

A validation study was conducted using data from three subjects in order to assess preservation of relative surface areas and distances between the original 3D geometry and the flat map geometry. In order to assess relative surface areas in the two geometries, areas were computed for the pulmonary vein and appendage ostia in both the original and flat map geometry. The ratios $R_i = \frac{A_j}{A_k}$ where $j = 1, \dots, 5$ and $k = j + 1, \dots, 5$ are computed in both geometries. A_j and A_k are the computed surface areas for each of the four pulmonary vein ostia and the appendage boundary. A total of $i=10$ surface area ratios were computed per subject.

In order to assess relative distances, image fiducials were generated at six locations across the posterior wall of the left atrium as shown in Figure 2. Fiducial locations were as follows: between the left superior pulmonary vein and left atrial appendage, carina between left superior and left inferior pulmonary veins, inferior to the left inferior pulmonary vein, inferior to the right inferior pulmonary vein, carina between right superior and right inferior pulmonary veins, and superior to the right superior pulmonary vein. Each subject was mapped to the standardized reference space with the image fiducials. Distances between the center of each pair of image fiducials were computed on both the original 3D geometry as well as the flat map geometry. In the flat map geometry, standard Euclidean distances were computed and in the original 3D geometry, curvilinear distances were computed along the surface of the left atrium. The ratios $R_i = \frac{d_j}{d_k}$ where $j = 1, \dots, 15$ and $k = j + 1, \dots, 15$ are computed in both geometries where d_j and d_k are the distances between the center of each pair of image fiducials. A total of $i=15$ distance ratios were computed per subject.

Generation of Probabilistic Map

A probabilistic map was computed across a population of 10 subjects as follows. One subject was randomly chosen as the atlas and maps were generated in the standardized space for each subject using the proposed technique. Probabilistic maps were generated by computing $N_i/10$ for $i = 1, 2, \dots, 5$ at each voxel in the standard image space where i is each of the four pulmonary veins and the appendage and N is the number of times an anatomic structure was projected to that voxel location. Values in the probabilistic map can range from 0.0 - 1.0, where 0.0 indicates that none of the subjects had the anatomic structure at that location, and 1.0 indicates that all subjects had the anatomic structure at that location.

3. RESULTS

A plot of the surface area ratios computed in the original versus the flat map geometries is shown in Figure 3(a) where each subject is plotted in a separate color. The correlation coefficient between the area ratios in the two spaces is $r=0.81$. Overall, surface area ratios appear to be preserved reasonably well in the flat map space as compared with the original geometric space. A plot of the curvilinear distance ratios versus the flat map distance ratios is shown in Figure 3(b) where each subject is again plotted in a separate color. The correlation coefficient between the distance ratios in the two spaces was $r=0.80$. Distance ratios appear to be preserved overall, with a larger spread for higher ratios. This is likely due to the fact that the larger ratios will contain one longer distance which may have more variability between the two spaces.

A combined probabilistic flat map across 10 subjects for the pulmonary vein and appendage ostia is shown in Figure 4. Red indicates a high overlap (1.0) and blue indicates a small overlap (0.1). In this map, overlapping regions between individual probabilistic maps are excluded and colored black in the figure. The probabilistic map demonstrates that the location of the inferior ostia have higher variability than the superior ostia and the variability of the left atrial appendage is similar to the superior pulmonary veins.

4. DISCUSSION

In this work, we described a novel technique for creating standardized flat maps of the left atrial pulmonary vein ostia and appendage boundary. Relative surface areas as well as relative point-to-point distances were shown to be reasonably preserved on the flat map geometry as compared to the original geometry. In the present work, the camera viewpoint was empirically determined from the atlas subject and held constant for all other subjects. In future work, we will investigate quantitative techniques for setting this location and assess its robustness in terms of flat map generation. An application of this method was demonstrated in which flat maps were combined into a standardized space to create a probabilistic map which quantifies inter-individual variability in both the location and configuration of left atrial ostial anatomy. These type of maps could potentially be used to distinguish normal versus abnormal variability, or, when combined with clinical outcome data, to quantify correlations between success rates and pulmonary vein structure.

5. ACKNOWLEDGEMENTS

This research was supported by NIH grant RO1EB002834 from the National Institute of Biomedical Imaging and Bioengineering and NIH grants HL089709 and HL089645 from the National Heart Lung and Blood Institute.

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Figure 1.

Segmentation of the left atrium and pulmonary veins from (a) front and (b) back views. In (c), the segmentation has been modified to contain only the pulmonary vein ostia (shown from back view). (d) Flat map of pulmonary vein and appendage ostia. Note that the camera is located at the anterior end of the left atrium, that is, looking from the front as in Figure 1(a). Left atrium (yellow), right superior pulmonary vein (magenta), right inferior pulmonary vein (blue), left superior pulmonary vein (red), left inferior pulmonary vein (green), left atrial appendage (purple).

Figure 2. Image fiducials (in white and circled in red for easier visualization) used for validation study.

Figure 3.

(a) Area ratios on original geometry versus flat map geometry. (b) Line ratios on original 3D geometry versus flat map geometry. For both plots, measurements from each subject are shown in different colors and the fitted line is shown in black.

Figure 4.

Combined probabilistic map of pulmonary vein ostia and left atrial appendage locations.

RSPV=right superior pulmonary vein, RIPV=right inferior pulmonary vein, LAA=left atrial appendage, LSPV=left superior pulmonary vein, LIPV=left inferior pulmonary vein.

Figure 5.

(a),(b) Views of the left atrium (in white), pulmonary vein ostia, and appendage boundary in the context of the 3D volumetric data. (c) Left atrium, pulmonary vein ostia, and appendage boundary unwrapped onto a flat map. Color scheme for pulmonary vein ostia and appendage boundary are the same as Figure 1.