Abstract
The planning of cryo-balloon ablations for treatment of atrial fibrillation is a crucial task for a physician as he has to determine which size of the balloon catheter is required for isolation at each pulmonary vein. Today, the diameter of the pulmonary vein’s ostium is measured in a pre-operative data set to determine which type of catheter is most appropriate. We present a novel tool that visualizes a cryo-balloon catheter model within a 3-D model representing a segmented left atrium. Using this approach, physicians are able to better assess the catheter fit. So far, measurement of the pulmonary vein diameters have been performed by evaluation of 2-D slices taken from pre-operative data sets. The first feedback obtained by physicians was very encouraging as this tool offers better insights for balloon catheter ablation procedures.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality

1. Introduction

Atrial fibrillation (AFib) is widely recognized as the most common heart arrhythmia [CBP07, CAM011]. It is also on top of the list of diseases that are considered as a leading cause of stroke [GWS01, WAK91, FR11]. The first-line of treatment for AFib today is drug therapy. If drug therapy fails, then the second-line treatment option is electrical isolation of the pulmonary veins (PVs) attached to the left atrium [CBP07, BHS11, BSG11, BSH11]. The current minimally-invasive approaches typically rely on radio-frequency ablation catheters [HGF94] or on cryo-balloon catheters [AUR03, VJR07]. The cryo-balloon ablation technique was introduced to reduce risks related to radio-frequency catheter ablation such as pulmonary vein stenosis and esophageal fistula [DKCJ11, NVS08, BBY10]. If balloon catheters fit well to the anatomy of the left atrium, a contiguous circular lesion can be achieved very efficiently, thus simplifying the procedure and speeding it up as well. Catheter ablation procedures are performed in electrophysiology (EP) labs usually equipped with modern C-arm X-ray systems providing 3-D imaging of the heart [PHL09]. Augmented fluoroscopy using a perspectively forward projected overlay representation of 3-D objects onto live fluoroscopic images has become a useful tool for navigation when performing ablation procedures [DME05, EDH08, EDDL08, BWL11]. Unfortunately, current navigation tools do not provide tools to localize and visualize cryo-balloon catheters in 3-D. Commercially available cryo-balloons come in two different diameters, a 23 mm balloon and a 28 mm balloon [FO11]. It mainly depends on the patients anatomy, especially the configuration of the left atrium and the pulmonary veins, which balloon to choose. Different methods are proposed how to assess which balloon should be used depending on measurements in pre-operative data sets. Most of the time, only the diameter of the pulmonary vein is estimated, see Fig. 1 for an example. This measurement is cumbersome, and it may even be misleading. We propose the first method to assess 3-D cryo-balloon positions within a pre-operative 3-D data set. Using our proposed method, we can provide information to the physician which catheter size is more likely to fit.

In the first section of this paper, we briefly describe the standard procedure to determine the diameter of the pulmonary veins. In the second, we introduce our new approach...
using our atrial fibrillation ablation planning tool. In the last section we discuss the advantages and disadvantages of our approach.

2. Default Assessment

A pre-operative data set is required to assess which cryo-balloon catheter type can be used. Commercially available products such as *syngo* InSpace EP (Siemens AG, Healthcare Sector, Forchheim, Germany) are capable of segmenting the left atrium in pre-operative data sets such as CT [BBLP10], MRI [MHB10] or C-Arm CT [PHL09, BSY09a, SMB09, BSY09b], see Fig. 2 for a segmented MRI. This segmentation can also be used to determine the diameter of the ostium of the pulmonary veins. The assessment can be performed by using the combination of the segmentation and the pre-operative data set, see Fig. 3. Recently *‘the ratio between the maximal and minimal PV ostial diameter and the angle between the PV longitudinal and the frontal body axis’* has been proposed to assess which balloon has to be chosen [FO11]. But this increases the time required for a physician to determine which catheters are required during the procedure. To reduce the amount of a physician’s time required for the assessment and to provide a better visual feedback, we propose to use the segmented left atrium which is visualized in 3-D and to place a 23 mm and/or a 28 mm balloon catheter at the ostium of the pulmonary vein to visually perform the assessment.

3. AFiT

In this section, we summarize the Atrial Fibrillation Ablation Planning Tool. First, the visualization methods for the left atrium and the cryo-balloon are explained. Afterwards, some details on the positioning of the balloon and the carving view are presented.

3.1. Object Visualization

**Left Atrium Visualization** is achieved by loading and displaying a segmented 3-D mesh of the left atrium (LA). In our case, *syngo* InSpace EP (Siemens AG, Healthcare Sector, Forchheim, Germany) was used for segmentation. For testing of our software prototype, an MRI volume data set with 63 slices and a matrix size of $256 \times 256$ was used. Each voxel of the volume was of size $1.03\text{mm} \times 1.03\text{mm} \times 1.62\text{mm}$ and was represented by 9 Bit. The segmentation result is stored as indexed face set in a .xml format. The .xml file contains information about the position of the object’s vertices and normals. Additionally, topological information about which vertices build a triangle is stored. To be able to display the segmented LA, the indexed face set was read out from the file and stored to a vertex-buffer-object (VBO). VBO’s combine the benefits of vertex-lists and display lists. The geometry information stored in an VBO is fast accessible and easy to update [AHH08]. Depending on the usage of the data, the memory manager can optimize the access and storage of the data. Static data, e.g., that is not changing can be stored directly in the high speed memory of the graphics-card. By doing so, large objects can be drawn very fast and further extension of the tool can easily be realized. To place the LA around the origin, the position of each vertex was translated by the mean of all vertices. Our tool provides the method to freely rotate the left atrium and also to zoom in and out. This visualization is represented in Fig. 4.

**Cryo-Balloon Visualization** is performed by using a sphere with a diameter of either 23 mm or 28 mm as catheter model. These sizes represent the available cryo-balloon diameters of the Arctic Front device (Medtronic CryoCath, Pointe-Claire, Quebec, Canada). The cryo-balloon models can be freely moved around and be positioned at the ostium of the pulmonary veins. To position the catheter, the catheter model needs to be selected and is then moved parallel to the viewing direction. Hence, our tool requires a rotation of the view to reach the desired position. By doing so, we make sure that our software is easy to use and the user is required to look from different positions at the left atrium. The balloon automatically occludes the mesh representing the left atrium. The position of the cryo-balloon with respect to the LA can be stored and loaded upon request. An example for the visualization is given in Fig. 5.

Transparency is achieved by changing the opacity of triangles that are facing towards the camera. Those triangles that are facing away from the observer are not changed. By doing so, we avoid that the left atrium is faded to black. Besides changing the transparency we provide a carving view. Carving means, that the front face of the left atrium is partially invisible to a certain degree. In the past years, the use of shaders has evolved to an established method in computer graphics because they provide a huge flexibility. Nowadays shaders are available and visualization pipelines do not need to comply with a standard rendering pipeline. More information about shader can be found in [RLG09]. To achieve a correct visualization of transparency, some drawing aspects have to be considered [WHSL10]. First of all, the LA has to be divided into two parts, one which consists of all back facing polygons, and one comprising all front facing polygons. The back facing part is usually not visible to the viewer. However, if the front becomes transparent or is cut out, the back face of the object will be visible as well. To this end, blending has to be enabled [Shf09]. During blending, the color of already drawn primitives is combined with the color of the incoming primitive which then results in a translucent looking material. An example of the visualization is given in Fig. 7 (a).

3.2. Carving View

In the following section, a vertex $p$ is considered as a point that is used to generate the mesh in 3-D, whereas a pixel $c$ is considered as an interpolated 3-D point on the mesh which
Figure 1: (a) MRI volume data of the left atrium (b) Manual measurement of the diameter of the left superior pulmonary vein.

Figure 2: (a) MRI volume data of the left atrium. (b) The same volume data set combined with the segmentation of the left atrium. The segmentation was performed using syngo InSpace EP (Siemens AG, Healthcare Sector, Forchheim, Germany).

will appear as an image pixel. To realize the carving effect, only the front faces of the LA are affected. The decision, whether a pixel of the mesh is visible or discarded depends on the pixel’s relative distance to the viewing position, which is set by the user. Before a pixel can be rejected, some information needs to be known. Besides the user-set carve factor $\rho_f \in [0, 1]$, which defines the degree of carving, the camera position $p_c \in \mathbb{R}^3$ needs to be known as well. In addition, the maximum distance of a pixel to the origin $d_{\text{max}} \in \mathbb{R}$ is
Figure 3: (a) Assessment of the diameter of the four pulmonary veins by considering only the segmentation result. (b) Assessment of the diameter of one pulmonary vein by considering the combination of the segmentation and the pre-operative data set.

Figure 4: (a) Visualization of the left atrium. (b) Visualization of the left atrium after rotation and zoomed in.

estimated by

\[ d_{\text{max}} = \max_i \| p_i \|_2 \]  

(1)

with the mesh vertices \( p_i \in \mathbb{R}^3 \). An illustration of the orthographic projection and the distances required for the calculation of the carving is given in Fig. 6. The position of a mesh vertex \( p_i \), with \( i \in \mathbb{N} \) the number of mesh vertices, is known. In our case, \( N \) is about 20,000. This distance is calculated
Figure 5: (a) Visualization of the 23 mm balloon positioned at the left inferior pulmonary vein. (b) The same pulmonary vein with a 28 mm balloon at the same position.

Figure 6: Illustration of the orthographic projection and the distances used for carving. The maximum distance $d_{\text{max}}$ of a mesh vertex to the origin is calculated only once during mesh loading. The minimum distance $\hat{d}_{\text{min}}$ of a mesh vertex to the camera is estimated by the subtraction of $d_{\text{max}}$ from $d_{c}$, with the distance of the camera to the origin as $d_{c}$.

only once while the left atrium is loaded. Since the mesh is centered at the origin, it is sufficient to calculate the norm of each loaded vertex and store only the vertex with the maximal distance. As previously mentioned, the left atrium is centered around the origin and an orthographic projection is used. Thus, the maximal distance $d_{c} \in \mathbb{R}$ that a front facing pixel can have to the camera, is equal to the distance between the camera and the origin, which is given as

$$d_{c} = ||p_{c}||_{2}. \quad (2)$$

Next, the minimum distance between a front facing pixel and the camera has to be determined. Since this distance depends on the current geometrical shape of the LA, we approximate this distance by calculating the overall minimal distance $\hat{d}_{\text{min}} \in \mathbb{R}$. As $d_{c}$ is known, we can derive

$$\hat{d}_{\text{min}} = d_{c} - d_{\text{max}}. \quad (3)$$

In camera space, the distance $d(q_{j}) \in \mathbb{R}$ between the current processed mesh pixel $q_{j} \in \mathbb{R}^{3}$, with $j \in \mathbb{N}$ and the camera center is determined as

$$d(q_{j}) = ||q_{j}||_{2}. \quad (4)$$

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The ratio $\rho \in \mathbb{R}$ that describes the relative distance of a mesh pixel is obtained by

$$\rho = \frac{|d(q_j) - d_{\text{min}}|}{d_{\text{max}}}. \quad (5)$$

A comparison of $\rho$ with the current carve factor $\rho_f$ is used to decide whether a vertex shall be discarded or not. An example of the visualization is given in Fig. 7 (b). As the maximal distance of a vertex to the origin is calculated only once, our method requires only one rendering pass. This approach is similar to the importance driven visualization proposed in [VKG04, VKG05].

4. Discussion and Conclusions

Using AFiT, a physician can get direct 3-D visual feedback to determine which type of cryo-balloon catheter should be used for the procedure. The visualization is performed using a segmented left atrium. The first feedback obtained from electrophysiologists, who were involved in the development of AFiT, was very encouraging. Our proposed tool is easy to use and the visualization helps to find the correct balloon catheter for the procedure. Nevertheless, more feedback and a clinical evaluation are needed to quantify the clinical impact of this new planning tool. Nevertheless, our tool could help whenever a 3-D device needs to provide any feedback about wall contact. This has to be assessed manually by the physician. Deformation of the LA up to a certain extent may be beneficial. In addition to that, our catheter models can currently be placed literally anywhere even if the position is not directly accessible. Feedback should be provided automatically if the catheter can be positioned at the planned position or not.

Apart from that, one could assess the clinical value using an augmented fluoroscopy technique to reconstruct a balloon-catheter during the procedure within a pre-operative data set is presented in [KBB*11]. The value of fluoroscopic overlay images for radio-frequency catheter ablations has been proven [EDH*08, DME*05, BLHS09, BWL*10, BLSH10, BLHS10]. An extension of AFiT to cover other single-shot devices, such as the pulmonary vein ablation catheter (PVAC, Medtronic Ablation Frontiers LLC, Carlsbad, CA, USA), or the multi-array ablation catheter (MAAC, Medtronic Ablation Frontiers LLC, Carlsbad, CA, USA) is also conceivable. Focusing on intra-procedural visualization, catheters as the force-sensing catheter are also of interest [KLK*11]. Further extension could also focus on different interventions, such as transcatheter aortic valve implantation [SKH*11] or stent placements [RES*07, RPS*09, ZIL*10, JLZ*10]. In general, one could say, our tool could help whenever a 3-D device needs to...
to be placed and the diameter of the device has to be determined beforehand.

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References


