Automatic Segmentation of the Left Atrium

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Abstract. Segmentation of the left atrium is vital for pre-operative assessment of its anatomy in radio-frequency catheter ablation surgery, which is commonly used for treating atrial fibrillation. In this paper we present an automatic approach for segmenting the left atrium and its pulmonary veins from MR angiography (MRA) data sets. Based on the notion that in MRA the atrium becomes connected to surrounding structures via partial volume affected voxels and narrow vessels, the atrium can be separated if these regions are characterized and identified. The blood pool, obtained by subtracting the pre- and post-contrast scans, is first segmented using a region-growing approach. The segmented blood pool is then subdivided into disjoint subdivisions based on its Euclidean distance transform. These subdivisions are then merged automatically starting from a seed point and stopping at points where the atrium connects to a neighbouring structure. The resulting merged subdivisions produce the segmented atrium.

1 Introduction

One of the most common causes of deaths in patients with cardiovascular related illnesses are heart strokes and attacks. The American Heart Association reports that 15% of all heart strokes are caused by a life-threatening condition called atrial fibrillation (AF) [1]. AF is a condition involving the left atrium of the heart. The left atrium is one of the four chambers of the heart. It receives oxygenated blood from the lungs and pumps it into the left ventricle. This blood is then circulated to the rest of the body. In a healthy adult the left atrium pumps blood into the ventricle in a regular rhythm. In AF, the left atrium quivers in an abnormal rhythm and is no longer able to pump blood into the left ventricle efficiently. This may cause possible pooling and clotting of blood in the left atrium which can lead to a stroke. Radio-frequency catheter ablation (RFCA) has become the treatment of choice for patients suffering from AF [2]. The objective of the ablation procedure is to eliminate sources of *ectopic foci* by charring tissues with high radio-frequency energy. These sources are identified pre-procedurally by examining electroanatomical maps that correlate the eletrophysiological characteristics with the endocardial anatomy. Medical literature indicates pulmonary venous drainages of the left atrium to be strong sources of ectopic focal activity [8]. Thus, a correct segmentation of the left atrium and its pulmonary venous drainages is important at this stage for planning the surgical procedure and also to allow the integration of the electroanatomical data with cardiac imaging data.

The left atrium is a highly anatomically variable structure where the number and sizes of the pulmonary venous drainages can vary significantly across patients. Variations to the right and left drainage patterns of the atrium have been documented in [3]. This high degree of variability makes left atrium segmentation difficult. Little work has been done on automated left atrium segmentation. Berg et. al. [4] uses a shape-constrained deformable surface model to segment the left atrium from multi-slice CT images. However, the model is restricted to a mean surface model which is built from training samples. Although such a technique may perform well on the commonly occurring variants of the atrium, the under-representation of the rarely occurring variants in the mean model makes it difficult for it to fit to these instances. John et. al. [5] uses a data-driven approach for segmenting the atrium from MR Angiography (MRA) datasets. The segmented blood pool is subdivided into regions which are later merged but separated at narrowings. This technique is based on the notion that the atrium is commonly connected to neighbouring structures through a narrowing. Although the method is fast and robust, it suffers from several limitations such as its inability to segment in cases where there is a non-narrow connection between a pulmonary vein and the pulmonary artery caused by a string of partial volume affected voxels. Our method is similar to the one described in [5]. An important difference is the manner in which our system can correct for over and under-segmentations using very little user-interaction. A second difference is the calculation of saddle points in [5] which is replaced with finding a point with the highest Euclidean distance value in the separating surface between any two adjacent subdivisions. This gives the true diameter of the separating surface. A third difference is the use of automatic threshold selection for segmenting the blood pool which has greatly improved the quality of our results.

2 Segmentation

The images acquired for this study are MRA images. In these images, the atrium is enhanced along with the pulmonary veins, pulmonary artery and aorta. Surrounding structures such as bones and other organs can also appear

in the MRA sequences and these are easily removed by subtracting the post- from the pre-MRA scans. The input to our segmentation system is thus the subtracted image showing only the enhanced vessels.

2.1 Segmenting the blood pool

Although, subtracting the post- from the pre-MRA scans removes bone and other irrelevant structures, it is still necessary to extract the blood pool and further remove neighbouring enhanced structures as much as possible in order to reduce the computational steps involved in determining the subdivisions. The left atrium is surrounded by neighbouring structures such as the pulmonary arteries, ascending aorta and the left ventricle. During acquisition, blood which is contrast-enhanced perfuses into these regions very quickly making it difficult to avoid imaging these neighbouring structures. These neighbours can be partly removed by using a bounding box which selects a region of interest around the left atrium, thereby excluding the unwanted structures as much as possible. The blood pool within the bounding box is extracted using a region-growing segmentation technique where a seed point inside the atrium is selected. The lower and upper thresholds for blood are automatically computed using the Otsu method [6]. In this method an optimal threshold value which maximizes the *between-class* variance between blood and non-blood tissue classes is determined. The output at this stage is a binary image with the segmented blood pool that contains the left atrium, its pulmonary venous drainages and segments of neighbouring vessels and structures. Although it is not vital to remove the ventricle blood pool in the context of RFCA, the bounding box can cut off the atrium from the ventricle blood pool along a suitable user-defined plane.

2.2 Computing subdivisions

The blood pool is subdivided into regions using a scheme described below. Neighbouring subdivisions are later merged automatically to give the segmented atrium. The process of subdividing the blood pool is done in three steps: 1) Computing the Euclidean distance transformation of the image. 2) Finding local maximums on the EDT map. 3) Determining subdivision membership for each voxel in image.

In the first step we compute the Euclidean distance transformation (EDT) of the binary image. Given that we have a distance metric defined, a distance transformation is an assignment of each voxel to a distance. This distance is the closest distance of a voxel to the background voxel. Defining the metric to be the Euclidean distance between any two points, the EDT can be computed for our binary image. It has recently been possible to compute the exact EDT of a binary image in linear time and we use the algorithm described in Maurer et al. [7]. Under the EDT transformation, a voxel deep inside the blood pool gets a high distance value whereas a voxel in the proximity of a boundary gets a relatively smaller value. Voxels outside the blood pool is assigned a distance value of zero.

The next step is to compute the local maximum points on the EDT map. A voxel is a local maximum if its EDT value is greater than the EDT value of all its neighbours. We use a 26-voxel neighborhood, for calculating local maximums. The spatial distribution and frequency of these local maximum points is of interest. There are a large number of local maximum points in structures that are narrow and small such as the blood vessels which includes the pulmonary venous drainages to the left atrium. Wider structures such as the body of the atrium have a relatively smaller number of local maximums. This is due to the geometric nature of the EDT transform. Once the local maximum points are determined, for each voxel we compute the subdivision it belongs to. Starting from the voxel we search along the path with increasing EDT values until we reach a local maximum. The voxel belongs to the subdivision that is centred by this local maximum. In this way each local maximum produces a subdivision which is generally composed of voxels surrounding it. Figure 1(ii) shows an MRA slice subdivided using the described subdivision scheme.

2.3 Subdivision Merging

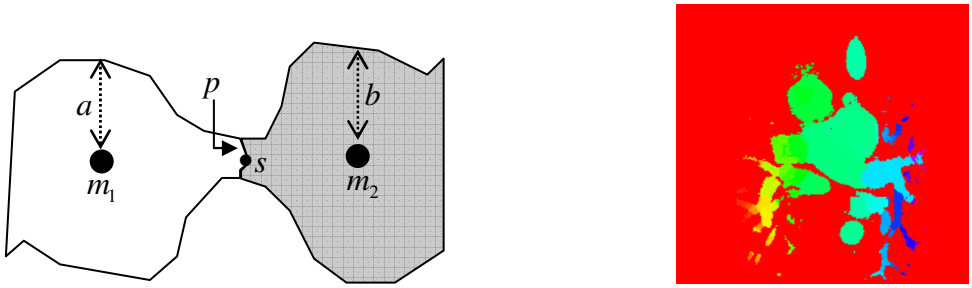
Once the subdivisions are computed, they can be merged interactively and manually by the user. Assuming that the user has some knowledge about the shape of an atrium, subdivisions inside the atrium can be manually chosen by selecting the local maximums which uniquely identify them. This is a semi-automatic approach for segmenting the left atrium. The user selects the local maximums based on a visual assessment of whether it lies inside or outside the atrium. This visual assessment is possible by overlaying the local maximum points on the original MRA of the segmented blood pool. In a next step, the selected subdivisions are merged, giving the segmented atrium. The complexity of this manual procedure depends on the number of local maximums or subdivisions. As described earlier, due to the way the local maximums are spatially distributed, more subdivisions occur within the pulmonary venous drainages than around the body of the atrium. This makes the task of selecting the subdivisions easier and quicker within the body of the atrium and relatively harder and slower at the pulmonary veins. Although this manual technique can be slow; however, when performed correctly it gives good segmentation results. Alternatively, the

subdivisions can be merged without any user intervention by using an automatic scheme described in the following section.

2.4 Automatic Subdivision Merging

Physically the left atrium is only connected to the left ventricle through the mitral valve. However, in MRA images, due to the partial volume effect the blood pool in the atrium becomes frequently connected to the blood in the ascending aorta. Additionally, the pulmonary venous drainages also appear connected to the pulmonary artery. Any left atrium segmentation scheme must be robust against such artefacts. It can be safely assumed that these connections are very narrow regions connecting either sides of a blood pool. The subdivision scheme described in the previous section will produce subdivisions on either side of such narrowings. It now merely remains to describe a merging scheme which merges subdivisions not separated by such narrowings and stops merging subdivisions that are separated by a narrowing.

To detect a narrowing, we first define a size metric for the subdivisions. The size can be attributed by its diameter which is the Euclidean distance value of its centre. These centres, as described in previous sections, are local maximum points. There is also a separating surface between any two adjacent subdivisions. The size of the separating surface is proportional to its diameter value. This is the deepest point within the surface which also has the largest Euclidean distance value.



(i) (ii)

Figure 1: (i) Two subdivisions with their diameters and separating surface (ii) An MRA slice subdivided into disjoint subdivisions.

Consider the *diameters* of two neighbouring subdivisions m_1 and m_2 which are separated by a separating surface *s* (figure 1(i)). The diameter of a subdivision is the Euclidean distance value of its local maximum. Assuming that *a* and *b* are the diameters of two neighbouring subdivisions with the separating surface diameter denoted by *p*. A merging criterion can be described in terms of a merging value which is defined as:

$$\text{merging value} = \min(a,b) - p \tag{1}$$

The merging value can be controlled using a user-defined threshold. The merging criterion allows any two adjacent subdivisions to be merged when their merging value satisfy a threshold. It prevents merging of subdivisions where the merging value falls below the threshold. In this way, the diameter of the separating surface at a narrowing will have a smaller diameter compared to the diameters of the adjacent subdivisions, thus yielding a large merging value. On the contrary, at non-narrow connections, the diameter of the separating surface will be comparable to that of its adjacent subdivisions, thus giving a smaller merging value. Selecting an appropriate threshold value will thus stop the merging process at possible narrowings.

The merging process starts from a user-selected seed point, preferably located close to the centre of the atrium. The subdivision containing the seed point is our seed subdivision. Similar to a region-growing approach, all subdivisions connected to the seed subdivision are merged on the condition that they fulfil the merging criterion. Symbolically, merging two subdivisions is equivalent to replacing them with a single subdivision with a diameter equal to the larger of the two diameters. At the end of the merging process the resulting merged subdivisions is the segmented atrium separated from the rest of the connected structures.

3 Results

We have tested our segmentation technique on 12 patient MRA datasets. The datasets acquired were diverse in terms of the anatomy of the left atrium and its pulmonary veins. One of the datasets had an abnormal enlarging of the left atrial body (figure 2(i)), and one of them had an un-documented and unusual left drainage where the two left pulmonary veins joined into one vessel (figure 2(iii)). The technique was robust against these cases and all cases were segmented successfully. The segmentation results were evaluated by an expert clinician by overlaying the segmentation on the original MRI and noting the differences. An important criterion for a good left atrial segmentation for RFCA is that it must include all the pulmonary veins to the left atrium. Missing a pulmonary vein can lead to an unsuccessful RFCA procedure where the patient can complain of recurring episodes of AF caused by the overlooked pulmonary vein [9]. The inclusion of all pulmonary veins in the segmentation was thus easily validated using this overlaying technique.

Once the EDT and subdivisions are computed, the segmentation process is almost instant taking less than a second for each MRA image. Computation of the EDT for the image is also very fast taking less than a second. However, subdivision computation can take a few seconds depending on the size of the dataset. The segmented images were visualized using a marching cubes isosurface reconstruction where the iso-value for blood was automatically selected using the Otsu method [6].

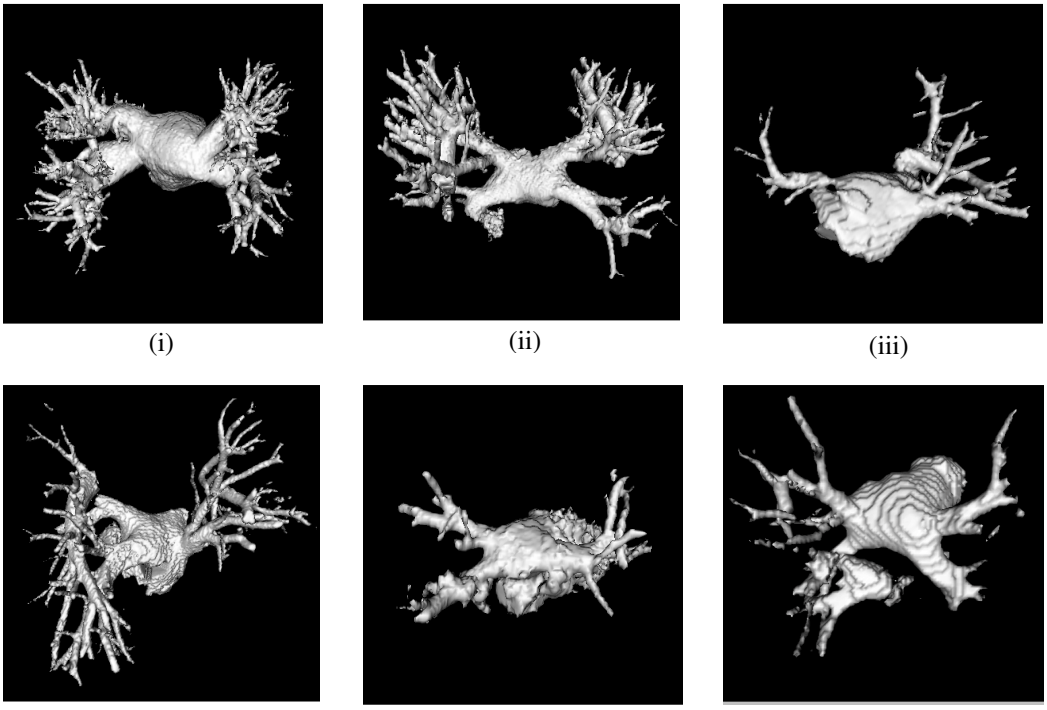


Figure 2: Marching cube iso-surface reconstruction of the segmented left atriums of 6 different patients. Note the variation in shape, size and anatomy of the atrium across patients.

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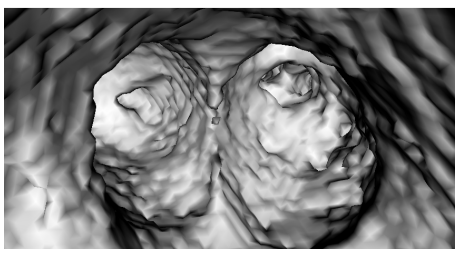

Figure 3: An endocardial of the segmented atrium of figure 2(i). The camera was positioned to face the ostia of the two pulmonary venous drainages to the right side of the atrium.

Electrophysiologists sometime also prefer an endocardial view where a clear view of the drainage openings are visible. This view is important for surgical planning allowing the circumferential path of ablation to be traced easily. Figure 3 shows one such view of the segmented atrium of figure 2(i) where the camera was positioned facing the two drainage openings to the right side of the atrium.

4 Discussions

Due to the high degree of anatomic variability in the left atrium un-predictable shape variations may occur and can make such a data-driven technique susceptible to mis-segmentation. In at least one of the patient data we have noticed narrow regions *within* the atrium (figure 2(i)). This causes the algorithm to cut part of the atrium off at the narrowing producing an under-segmented left atrium. If these narrowings are within an opening of a drainage, an entire pulmonary drainage will be excluded from the segmentation leading to possible surgical failure. However, mis-segmentations can be easily verified by overlaying the segmented image on top of the original MRA dataset.

Our system can easily correct under-segmentations. We do this by identifying a seed point in the missed region and running the algorithm to segment this missed region separately. A different merging threshold is often required. The original segmentation can then be combined with the missed region segmented separately to give the final segmented atrium. In a similar way, possible over-segmentations can also be corrected by identifying a seed point within the over-segmented region and running the algorithm to subtract this region. We have found the subdivision merging process leaking into the pulmonary artery in some instances thus causing the over-segmentation. In such cases, a seed point selected inside the pulmonary artery and running the algorithm with a new merging threshold value allows the over-segmented artery to be segmented and removed from the final segmentation. It is also important to select the right value for the merging threshold (eq. (1)). Selecting a slightly higher threshold than what is appropriate can easily lead to over-segmentation and cause the merging process to leak into neighbouring structures. There are yet no means of automatically selecting this threshold value, and we currently rely on a trial-and-error approach.

5 Conclusions

We have presented a technique for automatically segmenting the left atrium from MRA datasets. The technique exploits the fact that partial volume affected voxels in MRA can cause the atrial blood pool to become connected to the blood pool of neighbouring structures via narrow regions. The Euclidean distance transformation of the blood pool is produced and is used to schematically subdivide the image into disjoint subdivisions. These subdivisions are later merged automatically starting from a seed point and stopping at the partial volume affected narrowings, yielding the segmented left atrium. The system has been tested successfully on 12 diverse MRA patient datasets and the segmentation results have been validated qualitatively by an expert clinician. In future research, we will present our results on a larger collection of MRA datasets and also include a quantitative means for validating the segmentation results. We also intend to investigate the possibility of automatically locating the pulmonary veins in the segmented atrium and determining the diameters of their ostia using endocardial views (figure 3). This can be useful in RFCA where the eletrophysiologist is required to make such accurate measurements before circumferentially ablating around the tissues of the ostia.

6 References

1. "Risk factors for stroke and efficacy of antithrombotic therapy in atrial fibrillation: analysis of pooled data from five randomized controlled trials" *Archives of Internal Medicine* **154**. pp. 1449-1457, 1994.
2. M. D. Lesh, G. F. Van Hare, L. M. Epstein et. al. "Radiofrequency Catheter Ablation of Atrial Arrhythmias: Results and Mechanisms" *American Heart Association* **89**. pp. 1075-1089, 1994.
3. E. M. Marom, J. E. Herndon, Y. H. Kim et. al. "Variations in Pulmonary Venous Drainage to the Left Atrium: Implications for Radiofrequency Ablation" *Radiology* **230.** pp 824-829, 2004.
4. J. V. Berg & C. Lorenz. "Accurate left atrium segmentation in multislice CT images using a shape model" In *Proceedings of the Society of the Photo-Optical Instrumentation Engineers* **5747**. pp. 351-360, 2005.
5. M. John & N. Rahn. "Automatic-left Atrium Segmentation by Cutting the Blood Pool at Narrowings" In *Proceedings of MICCAI*. pp. 798-805, 2005.
6. N. Otsu. "A Threshold Selection Method from Gray-Level Histogram" *IEEE Transactions on Systems, Man. and Cybernet* **9**. pp 62-66, 1978.
7. C. R. Maurer, R. Qi, V. Raghavan "A Linear Time Algorithm for Computing Exact Euclidean Distance Transforms of Binary Images in Arbitrary Dimensions" *IEEE Trans. on Pattern Analysis and Machine Intelligence* **25**. pp. 265-270, 2003.
8. M. Haissauguerre, P. Jais, D. C. Shah et. al. "Spontaneous initiation of AF by ectopic beats originating in the pulmonary veins" *The New England Journal of Medicine* **339.** pp. 659-666, 1998.
9. H. Nakashima, K. Kumagai, H. Noguchi et. al. "Evaluation of the recurrence of Atrial Fibrillation after pulmonary venous ablation" *Japanese College of Cardiology* **40(3).** pp. 87-94, 2002.