Semi-Automatic Segmentation of the Left Ventricle in CINE MR Datasets by Linked Radial Active Model (LRAM)

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Abstract. Heart failures (cardiac infarction) are of increasing importance due to increasing life expectation. For clinical diagnosis parameters for the condition of hearts are needed and can be derived automatically by imaging processing. In this work we present an efficient method to segment the left ventricle (LV) in heart MR data from rats using two linked active contour models working in a spherical coordinate system. The initial model used for the active contour scheme is generated from user given points by a radial interpolation algorithm. The model was developed on healthy heart data and was tested on 15 different data sets and the results are presented.

1 Introduction

Heart failures (cardiac infarction) are of increasing importance due to increasing life expectation of humans. Experimental animal research in this field focuses on stem cells or engineered heart tissue to re-increase the myocardial function after an infarct. In vivo investigations of the heart anatomy and function can be best performed with MRI. This technique provides good tissue contrast, high spatial resolution, and sufficient time resolution. Using so called CINE MRI the heart motion can be imaged as a sequence of images during the heart beating cycle. Most parameters, established for evaluation of the heart function in the clinical routine (estimated elliptic model etc.) are suboptimal mainly because normally the heart is not fully evaluated in 3D. This is so, because the evaluation is done manually and time consuming already in 2D. Therefore, we developed semi-automatic algorithms to perform 2D as well as 3D + time = 4D segmentation of MRI datasets of healthy and infarcted rat hearts. The approach uses linked radial active contours, one for the heart outline (epicard) and one for the left ventricle (endocard).

Recently much attention in segmentation research is given to active models especially for heart segmentation [1, 2]. All approaches have to deal with the relative low SNR, artefacts common for MRI of moving organs, and the huge interindividual variability. An interesting approach is the statistical active contour scheme, STACS by Plupitiwirjaweh [3]. It is a hybrid method combining region and model based information by extending the energy minimizing function of the active contour to find a reasonable segmentation. Advantages are full automatic execution and good convergence even with imprecise initial contours as well as the robustness due to incorporation of edge, region and model information. But the algorithm is computational expensive (complex region based information) and the approach published only deals with single 2D slices. Therefore, we proposed the Linked Radial Active Model (LRAM) to overcome the problems mentioned. Herein we first cut down the calculation time by performing all calculations in the polar system at the same time ideally suited for rounded structures like the heart. The LRAM is a combination of two active surfaces interacting in a spherical coordinate system which can be used for segmentation in 3D. Initial models are obtained by semi-automatic polar interpolation of a few manually placed starting points for the epicard and the endocard. The energy-function of the classical snake is extended with a linking term for connecting both contours and a term for shape information. The segmentation results are comparable to manual segmentation of trained persons.

2 Material and Methods

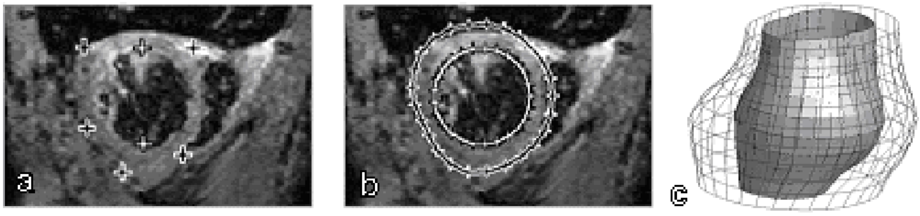
The heart scans of healthy and infarcted rats where obtained on a 4.7 T BRUKER Biospec 47/40. The CINE sequence used was: matrix 256 x 256, FOV 6 x6 cm, slice thickness 1.05 mm, TR = 30 ms, TEef = 3.5 ms, NEX 4, 13 to 22 slices per volume. Heart short axis slices were place based on reference scans and 4D heart datasets were obtained imaging slice wise through the heart (scan time about 1,5 h/rat). Since the rats (some severe heart infarcts) are under anaesthesia and should be measured repetitively the scan time was limited resulting in suboptimal image quality. The algorithm was tested on six healthy, four infarcted and five not classified rat heart data.

3 Algorithm

For initialization few points for the epicard and endocard are placed manually in three slices (Fig. 1 a). The initial contour is approximated by a radial interpolation scheme (Fig. 1 b) which is done for a number of equally spaced contour points by linear interpolation of the angle and the radius of the nearest user defined points in a polar coordinate system defined by the centroid of the user points. The points have to be set on the first and last slice containing the left ventricle as well as on one middle slice. For the third dimension another quadric interpolation is calculated between the corresponding contour points of two corresponding contours resulting in two 3d meshes (Fig. 1 c).

Next, the active contour algorithm is initialized with these two models by fitting an initial super elliptic model as described in [4] but without the free

Fig. 1. Example for user input (a) and radial interpolation result in 2d (b) and 3d (c)



form transformation capabilities. Now in an iterative greedy scheme the surfaces are optimized until the model energy is minimized or other abort condition (e.g. maximal number of iterations, minimal number of moved points) are reached.

During this process the contour points order is permuted every iteration to exclude systematic errors. The model energy is a combination of the inner and outer energies of the epicard and endocard surfaces and the linking energy in spherical coordinates.

$$
\begin{aligned}
E_{LRAM} &= E_{RAM}^{Endo} + E_{RAM}^{Epi} + E_{Link} \\
E_{RAM}^{Endo/Epi} &= w_1 E_{Smooth} + w_2 E_{SE} + w_3 E_{Grad} \qquad (1) \\
E_{Link} &= w_4 E_{Dist}^{global} + w_5 E_{Dist}^{local} + w_6 E_{Homogen}
\end{aligned}
$$

The energy for a surface is described by its smoothness which is minimal if all radii in a 4 neighbourhood of contour points are equal to the actual contour point. The energy related to the fitted super ellipsoid is calculated in its implicit form being minimal with all contour points lying on the ellipsoid. The third term often called outer energy uses gradient information to look for edges but could be replaced with any suitable function. The polar coordinate system with fixed angles reduces the gradient to lines from the centroids through the control points because control points are only allowed to move in these directions. The last term linking energy measures the distance of the two surfaces as the difference from the local and global average distance. To evaluate the space between the contour points of epicard and endocard the sum of gradients between them is build.

The segmentation error was obtained by comparing LRAM segmentation and manual segmentations to one single manual segmentation for each dataset. It is defined as the total sum of distances between corresponding points of the manual and automatic segmentations.

4 Results

It is well known that pre-processing of data is useful to get rid of many problems related to noise and artefacts in the data. Although different pre-processing strategies were tested, no significant improvement compared to the raw data was obtained. Though, the transformation from Cartesian to spherical space does some basic filtering by bilinear interpolation.

The number of control points has major effect on the results and a good choice in our hands is 30 to 50 points per contour per slice. Although the endocard is smaller its contour often needed more points to get the best segmentation performance. This can be explained by smaller details in the shape of the endocard.

Seven trained persons independently segmented one healthy and one infarcted heart. For the healthy heart the mean error across all subjects is about 1.5 ± 1.5 pixels. For the infarcted heart the mean segmentation error and standard deviation was just 1 pixel. The manual segmentation for infarcted hearts is better compared to the healthy hearts.

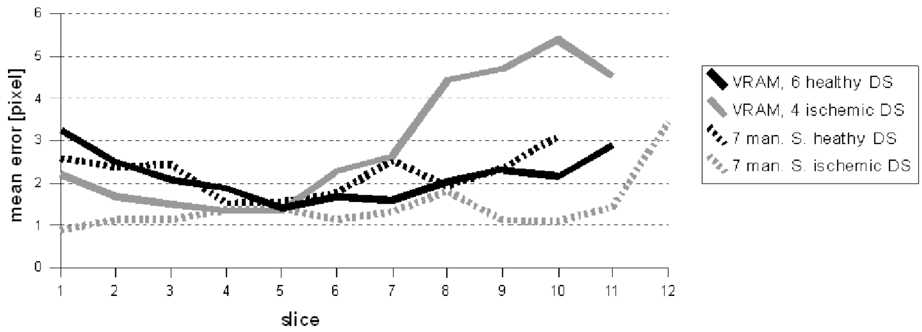
The segmentation behaviour of the LRAM mainly depends their initialisation and the weights for the energies. Variations of a single weight did not result in significant differences in segmentation (mean error always within 1-2 for inner slices and 3-4 for outer slices with infarcts), variations of more parameters did (details not shown here). On the other hand different initialization show stronger but alos minor effect on the final model. The mean error across different initializations was between 1 and 4 and the standard deviation 1 to 2. Repeating the segmentation with the same initialization obviously resulted not in identical but quite similar results.

Fig. 2 summarizes the direct comparison of all seven manual segmentations and the LRAM algorithm. In all cases better segmentation results were obtained in middle slices and worse results in the infarct areas (slices 8-11). Comparing LRAM and manual segmentation LRAM slightly performs better for healthy hearts. For the infarcted hearts the performance of LRAM was worse. The LRAM segmentation at different times of the beating cycle revealed slightly better results for diastolic compared to systolic phases. The LRAM approach is faster compared to manual segmentation and shows fast convergence behaviour already after 10-15 iterations. For one volume the user needs about 5 minutes to set initial points and the algorithm needs about 18-22 minutes (1 GHz Athlon, non optimized code). For manual segmentation the time was about 40-50 minutes.

5 Discussion and Outlook

We could show that LRAM incorporating geometric a priori knowledge (superellipsoid model, geometric constrains between the linked snakes) results in semi-automatic, robust and fast segmentations of the rat heart even for the low SNR MRI images here (limitations in acquisition time). Handling the geometry in a spherical coordinate system resulted in efficient algorithms especially suited for round objects. Linking snakes increased the overall segmentation stability considerably.

Fig. 2. Comparison of manual segmentation and LRAM for healthy and ischemic data



The reliability of LRAM segmentation is comparable to manual segmentation, even better for healthy but slightly worse for infarcted hearts. This might be due to fact that the parameterisation for the LRAM was developed for healthy hearts. It has to be adapted to the infarcted hearts by emphasizing local geometric aspects e.g. less wall thickness in the infarct region.

Because all datasets contained incomplete left ventricles (LV) the interpolation scheme resulting in open meshes works well. For datasets with complete heart and LV it needs to be modified to give closed model.

Up to now the temporal aspect of the data, the beating of the heart volume, is treated by sequential segmentation of the single volumes. By adding a time dimension to the model the adaptive optimisation of the geometry can be extend over the time domain ensuring corresponding contour points in space and time.

The energy term of LRAM might be extended by factors for acceleration and/or direction of movement. To minimize the user input for initialisation a statistically derived model could be established. Extending the linking with contours for the pericard or the right ventricle might increase the overall segmentation robustness.

References

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