A LEVEL SET METHOD FOR CONVEXITY PRESERVING SEGMENTATION OF CARDIAC LEFT VENTRICLE

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ABSTRACT

In this paper, a level set method is proposed for the segmentation of Left Ventricle (LV) from short-axis cardiac magnetic resonance images. According to the anatomical knowledge of LV, we first propose a convexity preserving mechanism to keep the shape of the evolving contour convex during the curve evolution, and thereby improves the segmentation accuracy. Then, the mechanism is incorporated into two-layer level set method to delineate endocardial and epicardial boundaries simultaneously. The proposed method has been quantitatively validated on a public dataset, and experimental results and comparisons with other methods demonstrate the superior performance of our method. Furthermore, such a generally constrained convexity-preserving level set method can be useful in many other potential applications, as validated by experiments.

Index Terms— Left ventricle segmentation, level set method, convexity preserving

1. INTRODUCTION

Segmentation of Left Ventricle (LV) from cardiac short-axis Magnetic Resonance Images (MRIs) provides important information for the diagnosis and treatment follow-up of Cardiovascular Diseases (CVDs), the leading cause of death worldwide[1]. The task of segmenting LV involves the delineation of endocardial and epicardial boundaries. In many clinical routines, the segmentation is often performed by experts manually, which is time-consuming and subject to intra- and inter-observer variations [1]. Automatic or semi-automatic segmentation of LV is thus highly desired. Although plenty of segmentation methods have been proposed, LV segmentation remains a challenging task.

Automatic and semi-automatic LV segmentation methods can be roughly classified into three categories: 1) statistical shape prior models [2, 3]; 2) atlas-based approaches [4, 5]; and 3) anatomical knowledge based algorithms [6, 7]. Statistical shape prior models often require a large amount of expert-segmented images to train the shape prior, which may be impractical in clinical practice. Atlas-based approaches do not require a training set for supervised learning, but they still need one or a few expert-delineated images to guide the segmentation on the target image, and they might not work in cases where the shape variation between the atlas images and the target is large. The proposed method belongs to the last category of algorithms, which can avoid training completely by imposing prior information obtained from the anatomical knowledge of the heart.

Level set method has been recognized as a powerful technique for image segmentation. Due to its desirable advantages, level set method has been applied in LV segmentation. Alessandrini *et al.*incorporated an annular shape prior in level set method to extract the whole LV myocardium[6]. Dietenbeck *et al.*used two hyperquadrics as shape prior to segment the endocardium and epicardium by using one level set function[7]. Lynch *et al.*utilized coupled level sets for segmentation of LV [8]. Feng and Li *et al.*proposed distance regularized two-layer level set (DR2LS) method for LV segmentation [9]. Liu *et al.*used edge-based level set method to extract the myocardial boundaries within the two-layer level set framework [10].

The incorporation of shape prior produces much more robust segmentation [11], convexity shape prior has attracted much research interest in recent years. Veksler and Thevenaz independently propose a specified convex shape prior into their segmentation frameworks[11, 12], the generality of these methods is thus limited. Though more general convex shape priors have been proposed[13, 14], the convexity energy in these methods is 3^{rd} order, which is hard to be optimized through level set method. Yet, to the best of our knowledge, we are the first to incorporate convexity shape prior in level set method.

In this paper, a convexity-preserving mechanism in the level set framework is proposed for LV segmentation without training any shape models for LV. With the convexity-preserving mechanism, the evolving contour is preserved to be convex during the curve evolution, and thereby improves the segmentation accuracy significantly. The mechanism is incorporated into two-layer level set method to extract endocardial and epicardial boundaries within a single process. Furthermore, such a generally constrained convexity-preserving

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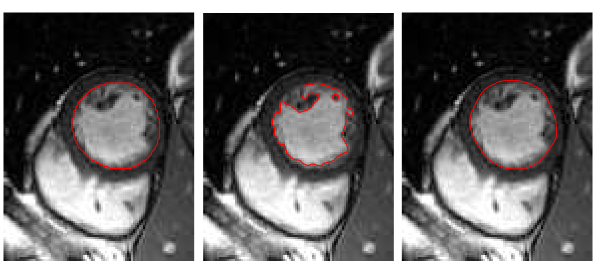
level set method can be applied in many other potential applications, as validated by experiments.

2. CONVEXITY-PRESERVING SEGMENTATION OF LEFT VENTRICLE

Due to illumination, occlusion and other factors, some information about the target may be lost during the imaging process. Segmentation of such images often requires the incorporation of shape priors to obtain robust results. Convexity is a generic shape feature in daily life, we thus propose a generally constrained convexity-preserving level set method which is further applied in the delineation of LV myocardial boundaries.

In cardiac MRIs, papillary muscles and trabeculae take similar intensities as the myocardium, as shown in Fig 1. A representative example of expert delineated endocardium is given in Fig 1(a). In clinical practice, the inclusion of papillary muscles and trabeculae in the LV cavity is more reproducible (i.e., agreed by most experts) [15]. Therefore, the desired endocardial and epicardial boundaries of LV should be convex and smooth for a better reproducibility. Segmentation approaches including level set methods might not obtain desirable boundaries of LV if the anatomical knowledge of the heart or shape prior information is not incorporated, as shown in Fig 1(b). In this section, we propose a convexity-preserving mechanism in the segmentation algorithm, which ensures the resulting boundaries to be convex in addition to being similar to the true boundaries, as shown in Fig 1(c).



(a) (b) (c)

Fig. 1. Convexity-preserving mechanism in LV segmentation. (a) expert-delineated endocardium, (b) segmentation result without anatomical knowledge, and (c) resultant endocardium.

2.1. Convexity-preserving level set

Let $\Omega \subset R^2$ be the image domain, $I : \Omega \to R$ be an image, and $\phi : \Omega \to R$ be a level set function. The curvature of ϕ is defined by

$$\kappa = div\left(\frac{\nabla\phi}{|\nabla\phi|}\right), \tag{1}$$

where $div(\cdot)$ is the divergence operator.

In order to keep the evolving contour convex, we define a Curvature Sign Indicator (CSI) function as

$$\beta(\kappa) = \begin{cases} 1, & \kappa \geq 0, \\ 0, & \kappa < 0. \end{cases} \tag{2}$$

The contour is convex at positions where $\kappa \geq 0$ and concave where $\kappa < 0$, as shown in Fig. 2. Through the CSI function, the propagating contour can be adaptively evolved to a convex contour.

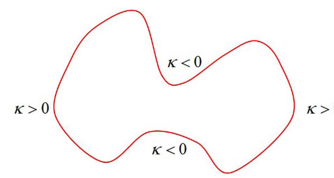


Fig. 2. Curvature of the evolving contour.

Regardless of the contour regularization terms, the following evolution equation with the convexity-preserving mechanism is introduced to evolve the level set function

$$\frac{\partial\phi}{\partial t} = \beta(\kappa)D(\phi; I) + \nu(1 - \beta(\kappa))\kappa\delta(\phi), \tag{3}$$

where $D(\phi; I)$ is the data term which attracts the evolving contour toward the desired object boundaries. The second term $\kappa\delta(\phi)$ is the convexity-preserving term, which allows bi-directional motions of the contour, i.e., it expands the contour where $\kappa < 0$ and shrinks the contour where $\kappa \geq 0$. ν is a nonnegative coefficient of the convexity-preserving term.

Eq. 3 indicates that, with the CSI function, the data term is disabled and the convexity-preserving term is activated where the contour is concave. Therefore, the contour is expanded and finally evolved into a convex one. On the other hand, at positions where $\kappa \geq 0$, the convexity-preserving term is disabled and the data term is activated, which ensures the convex parts of the contour are attracted toward the true boundaries.

The choice of the data term can be diverse, from region-based to edge-based level set methods. In this paper, we utilize the Distance Regularized Level Set Evolution (DRLSE) model [16] to propagate the contour. Thus, $D(\phi; I)$ can be obtained by

$$D(\phi; I) = \lambda\delta_\epsilon(\phi)div\left(g\frac{\nabla\phi}{|\nabla\phi|}\right) + \alpha g\delta_\epsilon(\phi), \tag{4}$$

where λ is a nonnegative coefficient of the length term, α is the coefficient of the balloon force term. δ is the Dirac function which is approximated by

$$\delta_\epsilon(x) = \frac{1}{\pi}\frac{\epsilon}{\epsilon^2 + x^2}, \tag{5}$$

and g is the edge indicator function defined by

$$g \triangleq \frac{1}{1+|\nabla G_\sigma * I|^2}, \tag{6}$$

where $G_\sigma * I$ filters I by a Gaussian kernel function.

It is worth noting that the proposed convexity-preserving mechanism can be easily combined with other level set methods due to its generality. And it can also be applied to segmentation of any other convex objects besides LV.

2.2. Convexity preserving level set for LV segmentation

In this section, the proposed convexity-preserving mechanism is further combined with the two-layer level set method[9] for LV segmentation. The two-layer level set method is particularly advantageous in segmenting myocardial boundaries for the following reasons. Firstly, the correlation between endocardium and epicardium is deployed to obtain accurate results. Secondly, different from the coupled level set method[8] which uses two level set functions to track the endocardium and epicardium, respectively, only one level set function is to be evolved. Endocardial and epicardial boundaries are represented by 0 level and k level of ϕ, as shown in Fig. 3. The red curve and the green one correspond to the endocardium and epicardium, respectively.

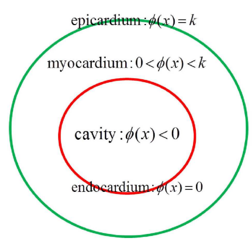


Fig. 3. Two-layer level set representation of LV.

As mentioned above, segmentation methods without the inclusion of papillary muscles and trabeculae in the myocardium produce results with the best reproducibility [15, 17]. According to this, the convexity-preserving mechanism is used to keep the two level contours convex. More precisely, the endocardial and epicardial boundaries of LV are obtained by the following evolution equation

$$\begin{aligned}\frac{\partial\phi}{\partial t} &= \beta(\kappa)[\lambda_0\delta_\epsilon(\phi)div\left(g\frac{\nabla\phi}{|\nabla\phi|}\right) + \alpha_0 g\delta_\epsilon(\phi) \\ &+ \lambda_k\delta_\epsilon(\phi-k)div\left(g\frac{\nabla\phi}{|\nabla\phi|}\right) + \alpha_k g\delta_\epsilon(\phi-k)] \\ &+ (1-\beta(\kappa))[\nu_0\kappa\delta(\phi) + \nu_k\kappa\delta(\phi-k)] + R(\phi), \end{aligned} \tag{7}$$

where λ_0 and α_0 are the parameters for 0 level contour, λ_k and α_k for k level contour, and ν_0 and ν_k are nonnegative coefficients defined previously. Note that the Eq. 3 and Eq. 7 are valid for both 2D and 3D images segmentation.

Due to the smoothly varying interval between myocardial boundaries, we propose the following distance regularization term $R(\phi)$ to keep the thickness between the two specified contours vary smoothly.

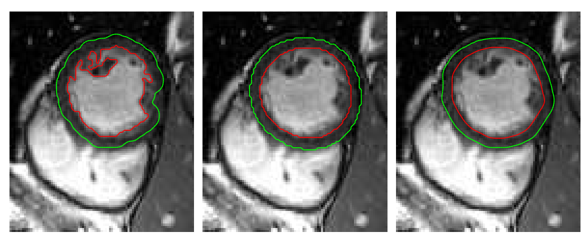
$$R(\phi) = \mu\left[\nabla^2\phi - N div\left(\frac{\nabla\phi}{|\nabla\phi|}\right)\right] \tag{8}$$

where N is set to a positive value. Although the real distance between the endocardium and epicardium varies at different positions, the proposed method can still obtain accurate approximation of myocardium thickness since $R(\phi)$ imposes a soft constraint on the evolving contour, which allows the distance between the two contours to be smoothly varying.

3. EXPERIMENTAL RESULTS

Unless otherwise specified, the parameters in this paper are set as follows: the time step $\triangle t = 1$, σ for Gaussian filter is set to 1, $\epsilon = 1$, $\mu = 0.4$, λ_0, λ_k, α_0, and α_k are set to 5, 0.5, -0.8, 0.1, respectively. Since the thickness of LV myocardium is chosen as 8. ν_0 and ν_k are both set to 1. For each image to be segmented, we use region growing to initialize the level set function.

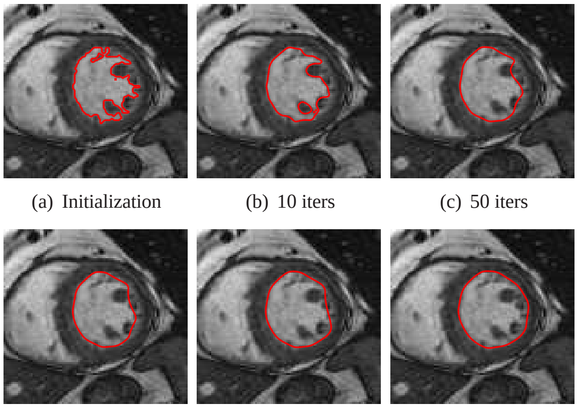
We first show result of our method on a cardiac MRI in Fig. 4. The initial contours are shown in (a), (b) and (c) respectively present the ground truth and resultant contours obtained from our method. From Fig. 4, it can be seen that the resultant boundaries are very similar to experts delineated contours.



(a) Initialization (b) Ground truth (c) Result

Fig. 4. Result of our method. (a) initialization. (b) experts delineated contours. (f) resultant endocardial and epicardial boundaries.

Fig. 5 demonstrates positive effects of the proposed convexity-preserving mechanism . The convexity-preserving level set method is applied to segment the endocardium only in this case. The initial contours are shown in (a), intermediate steps at iterations 10, 50, 100, and 200 are depicted in (b)-(e), (f) shows the final result. As we can see from (b), the evolving contour is firstly trapped at positions around boundaries of papillary muscles and trabeculae. With the convexity-preserving mechanism, the contour is expanded and finally pass through boundaries of tissues inside the LV cavity.



(a) Initialization (b) 10 iters (c) 50 iters

(d) 100 iters (e) 200 iters (f) Final

Fig. 5. Positive effects of the convexity-preserving mechanism. (a) initialization. (b)-(e) intermediate steps at iterations 10, 50, 100 and 200. (f) final result.

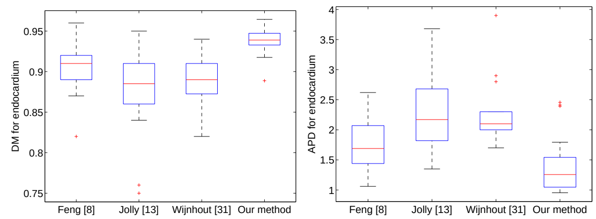
Our method has been validated on the training and validation data set for the Medical Image Computing and Computer-Asisted Intervention (MICCAI) 2009 grand challenge on left ventricular segmentation. Contour accuracies in terms of Dice Metric (DM) and Average Perpendicular Distance (APD) are used to evaluate the performance of our method. DM is defined as

$$DM(R_1, R_2) = \frac{|R_1 \cap R_2|}{|R_1 \cup R_2|} \tag{9}$$

where $|\cdot|$ is the area of a region. R_1 is the region segmented by the method to be evaluated, and R_2 is the region obtained from the ground truth. It can be easily seen that the closer DM is to 1, the better the performance of an algorithm is.

APD measures the distance from the contour obtained from an algorithm to the corresponding expert-delineated contours, averaged over all points. The smaller the APD is, the closer the two contours are. Box plots of the DM values and the APD values for the endocardium obtained from our method and three other approaches[9, 18, 19] are shown in Fig. 6. It can be easily concluded from the figure that the proposed method obtains a larger average DM value in addition to a smaller average APD value, which demonstrates the accuracy of our method. Moreover, the boxes shown in the box plot for the proposed method is relatively short which exhibits the much desired robustness of our method.

Finally, we demonstrate the potential of our convexity-preserving level set method. Fig. 7 shows an application of our method to face segmentation. The upper row shows the initialization, intermediate steps at iterations 20, 120, and final contour of DRLSE model with the incorporation of the convexity-preserving mechanism. The lower row depicts the intermediate steps at iterations 20, 120, 220, and final contour of the original DRLSE model. The two compared methods



(a) Boxplot of DM values (b) Boxplot of APD values

Fig. 6. Contour accuracy of endocardium in terms of DM and APD. (a) box plot of DM values. (b) box plot APD values.

share the same parameters and initialization given at the upper left corner. It can be seen from Fig. 7, our method obtains a quite desirable result in face segmentation.

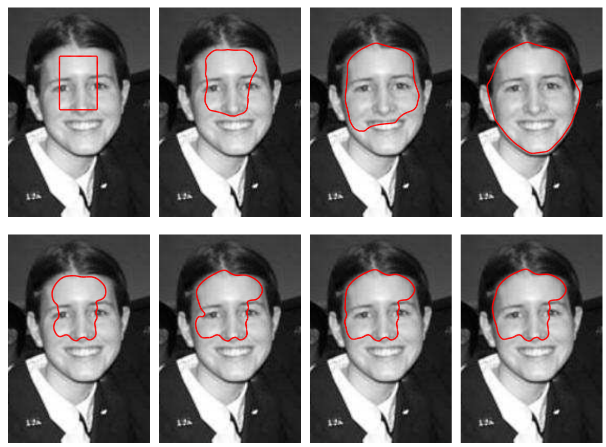


Fig. 7. Application of convex-preserving mechanism in face segmentation. Upper row: initialization, intermediate steps, and final results of our method. Bottom row: intermediate steps, and final results of DRLSE model.

4. CONCLUSIONS

In this paper, we first propose a generally constrained convexity-preserving level set method, which is further combined with the two layer level set method to simultaneously delineate endocardial and epicardial boundaries without training any shape models for LV. The shape of the evolving contour is preserved to be convex during the curve propagation, and thereby improves segmentation accuracy significantly. Experimental results and comparisons with other methods demonstrate superior accuracy and robustness of our method. Given the generality of its formulation, we expect that the proposed convexity-preserving mechanism will find its utilities in segmentation of ventricles from cardiac long-axis MRIs and many other applications.

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