Segmentation of the Left Ventricle from Cardiac MR Images Based on Radial GVF Snake

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Abstract

Segmentation of the left ventricle (LV) is a hot topic in cardiac magnetic resonance (MR) images analysis and still remains challenging. In this paper, we propose a novel method, radial gradient vector flow (GVF) snake, to segment LV automatically. Left ventricle centroid and region of interest (ROI) are located using temporal intensity difference along with Hough transform. Taking the centroid as an origin, the ROI could be transformed into polar coordinates where myocardium looks more like a horizontal band rather than a circle. This shape characteristic enables snake to evolve towards 1D radial direction instead of 2D image plane, which simplifies snake energy functions to 1D. A line-like shape constraint is adopted to conquer papillary muscle and weak boundaries. After endocardium extraction, GVF external force modified skillfully reactivates snake forward to epicardial contour successively. Several experiments are presented to demonstrate the effectiveness and robustness of the proposed method.

1. Introduction

Cardiac MR imaging is a noninvasive technique providing heart anatomical and functional information for diagnosis and treatment of cardiovascular diseases [1]. Segmentation of anatomic structures in cardiac MR images, especially the left ventricle, is prerequisite for computing diagnostic indexes such as ejection fraction, ventricular volume and wall thickening [2]. Manual segmentation is labor-intensive and time-consuming in clinical practice, thus it is imperative to develop an automatic method to extract LV contours.

Segmentation of the left ventricle remains one of the open issues because of partial volume effect, artifacts resulting from swirling blood, papillary muscle, noises and image anomalies. Many efforts have been devoted to solve this problem including morphologic segmentations [3], fuzzy clustering [4,5], model-based approaches[6,7], active contours[8~11], and level set methods[12]. Among others, active contour models or snakes become extremely popular and dominate this field from its debut in 1988[8]. For example, Ranganath [9] initialized the contour with the profile correlation matching method and tracked the LV endocardium in image sequences based on snakes. Makowski et al. [13] improved segmentation of complicated shapes such as papillary muscles in the LV by incorporating balloons to snake models. Siddiqui et al. [14] added a constant inflation term derived from minimizing certain weighted area energy functional to geometric snakes, extracting internal contours of LV and right ventricle(RV) simultaneously with a single initialization. Shin et al. [15] located the LV contours based on generalized gradient vector flow snake. Chen et al. [16] proposed generalized fuzzy GVF for the segmentation and robust tracking of the left ventricle in magnetic resonance images sequences.

In this paper, we present a novel automated method of extracting left ventricle contours from short-axis views of cardiac MR images, which is called radial GVF snake. First Hough transform is applied to intensity difference image computed between two consecutive frames in temporal image sequences to locate LV centroid and region of interest (ROI). Then the centroid is treated as an origin to transform the ROI into polar coordinates where myocardium looks more like a roughly horizontal band rather than an approximate circle. This characteristic of left ventricle enables snake elements to progress towards not 2D...
image plane but 1D radial direction. Consequently, snake energy functions simplify from 2D to 1D, which makes the model very simple and expedites contour evolution as well as discards the crossing problem \cite{17} in a natural manner. At the same time, a line-like shape constraint is employed to conquer papillary muscle and weak boundaries. Motivated by the work in \cite{18}, GVF external force is modified skillfully after endocardium location. Taking the endocardium as initialization, the new GVF force reactivates the snake forward to the epicardium successively.

2. Image Transformation

2.1. Automatic Localization

In a short-axis view of cardiac MR images, the myocardium is a dark area between two concentric circles enclosing a bright area corresponding to the blood in LV. On its left side is a bright region corresponding to the blood in RV. On its right side is a very dark area corresponding to the lungs. Under breath-hold condition, LV moves more obviously than its surrounding structures that are almost static during the cardiac cycle. This trait encourages intensity difference algorithm upon two consecutive frames in temporal image sequences to remove stationary background structures and then localizes the moving region of the left ventricle instances.

Suppose a cardiac MR images sequence \( I_{T}(x, y), (x, y) \) denotes the spatial coordinates of image point and \( t \in T \) is the time instant. The nearly non-moving background pixels in two consecutive frames from the temporal image sequences are excluded by the difference or subtraction operation,

\[
Var_{t}(x, y) = [I_{t+1}(x, y) - I_{t}(x, y)] > TH,
\]

where \( Var_{t} \) is the intensity difference image, \( TH \) is a threshold value below which we consider as non-moving background. It is estimated by the iterative thresholding method. Fig. 1(a) shows one of adjacent frames from a cardiac MR images sequence. In this sequence, myocardium moves along with heart beating; the chest cavity and lung change little due to breath-hold condition; and there exists the nearly non-moving image background. Fig. 1(b) displays the intensity difference image that represents the most dynamic region. Observing the image, the values near the myocardial boundaries are very different from other region because of larger movement of LV. The dense highlight inner circle-like region implies that endocardium moves faster than epicardium. Applying Hough transform to (b) results in a white circle (smaller) in Fig. 1(c). Centre of the circle denoted by a white dot is very close to the LV centroid and the radius indicates the size of blood filled region inside LV. In practice, the centroid lies on slightly right of the circle centre for the presence of papillary muscle; the larger white circle about three times radius in (c) encloses the whole LV and represents the region of interest (ROI) being discussed in the following section.

![Figure 1](image)

2.2. Polar Coordinates Transformation

The located LV centroid serves as an origin to transform the ROI into polar coordinates. Given a cardiac MR image \( I(x, y), (x_0, y_0) \) is the LV centroid and also the origin in polar coordinate system, \( R \) is the radius of ROI, then the transform image \( P(\theta, \rho) \) is expressed as

\[
P(\theta, \rho) = I(x', y'),
\]

\[
x' = x_0 + \rho \cos(\theta \frac{2\pi}{T}),
\]

\[
y' = y_0 + \rho \sin(\theta \frac{2\pi}{T}),
\]

\[
\rho = 1, ..., R; \theta = 1, ..., T
\]

where \( \rho \in [1, R] \) is the radial coordinates, \( \theta \in [1, T] \) is the angle coordinates, \( T \) is the circumferential sample frequency. Fig.2 illustrates the transform image after applying Eqs.(2) to the ROI. In the transform image, columns are corresponding to \( \rho \) and rows to \( \theta \). Upper bright region is the blood pool in LV. The middle dark horizontal band represents myocardium. Lower area lays the other tissues around LV such as the blood in RV, fat, lung and so on. This hierarchical structure and the special horizontal band shape of myocardium make it more convenient to segment LV in the transform image.
3. Segmentation of Myocardium

3.1. Review of GVF Snake Model

The traditional snake [8], or active contour model is a curve \( c(s) = (x(s), y(s)) \in \mathbb{R}^2 \) defined within an image domain that could cling to an object boundary or other desired features under the influence of internal forces within the curve itself and external forces derived from the image data, where \( s \in [0,1] \) is a normalized arc length. This curve evolves through the spatial domain of an image to minimize the energy functional

\[
E = \int_0^1 E_{\text{int}}(c(s)) + E_{\text{ext}}(c(s)) \, ds ,
\]

where \( \alpha \) and \( \beta \) are weighting parameters that control the snake’s tension and rigidity, respectively; \( c'(s) \) and \( c''(s) \) denote the first and second derivatives of \( c(s) \) with respect to \( s \). Using the calculus of variations, a snake that minimizes \( E \) must satisfy the Euler equation

\[
\alpha c''(s) - \beta c'''(s) - \nabla E_{\text{ext}} = 0 .
\]

Gradient vector flow (GVF) [10] field is the vector field \( v(x, y) = \frac{\partial E_{\text{int}}(c(s))}{\partial \rho} \) that minimizes the energy functional

\[
E_{\text{int}}(c) = \frac{1}{2} (|c'(s)|^2 + \beta |c''(s)|^2) .
\]

3.2. Radial GVF Snake Model

Due to its definition as a parameter function in \( \mathbb{R}^2 \), snake traces the motion of the elements in 2D image planes usually resulting in crossings in the contour during the energy minimization [17]. The crossing elements could move around the contour leading to the wrong evolution. Even the crossings can be detected, but only at the expense of computation time. Extracting the myocardial contours in the transform image avoids these problems subtly.

In the transform image, myocardial shape appears like a roughly horizontal band beginning from the left side to the right of the image as shown in Fig.2. This trait enables a line as snake contour initialization with a radial value smaller than the radius mentioned in Section 2.1. At the same time, the snake elements only need move along the radial direction to find the contour under the minimal energy without swing left or right. Formally, the angle coordinates \( \theta \) of the snake elements are invariant with the contour evolution.

\[
\theta_i = \theta_{r,1} .
\]

The radial coordinates \( \rho \) could be computed by discretizing eq. (5) and approximating the derivatives with finite differences. The corresponding Euler equation can be written as

\[
\rho_i = (A + \gamma \mathbf{I})^{-1}(\eta \rho_{r,i} - f_{\rho}(\theta_{r,i}, \rho_{r,i})) ,
\]

where \( A \) is a pentadiagonal banded matrix, \( \gamma \) is a step size, \( f_{\rho} = \partial E_{\text{ext}} / \partial \rho \). These two equations show that snake elements only need search along 1D radial direction rather than 2D image plane. Accordingly, the snake model is simplified to 1D expediting contour evolution. Owing to the elements parallel motion, the crossings could be readily solved in a natural manner.

3.3. Shape Constraints

During the process of LV segmentation, artifacts and papillary muscle as well as other image anomalies could make the snake contour strap in faulty edges or leak out from weak boundaries for the GVF snake models only catch the local geometrical features. In order to overcome the defects, global constraints about the object overall shape should be included.

Considering that the myocardium in the transform image looks more like a roughly horizontal band, a line-like constraint is incorporated into snake energies. The line-like constraint is given by

\[
E = \frac{\eta}{2} \int_0^1 (\rho(s) - \bar{\rho})^2 \, ds ,
\]
where \( \bar{\rho} = \int_0^1 \rho(r)dr \) represents the straight line and is dynamic with the evolution of the snake contour. This additional energy measures the deviation of the snake contour and pulls the contour close to the line maintaining the global shape feature of myocardium.

### 3.4. GVF field for Epicardium Extraction

The hierarchical structure in the transform image makes it easier to associate whether the epicardium could be extracted taking the resultant internal contour as initialization. It is well known that the snake contour would be stationary in the local minimum after the endocardium is located using the classical GVF force field. To segment the epicardium further, the local minimum that endocardial boundary lies should be erased from GVF external force field. Motivated by the work in [18], we keep the gradient in direction of \( \theta \) invariant and modify the gradient in direction of \( \rho \) as

\[
f_{\rho} = \max(P(\rho), 0) .
\]

Fig.3(a) shows the usual \( f_{\rho} \) edge map, (b) is the modified \( f_{\rho} \). It is obvious that the internal contour lost after modification by eq.(10). (c) depicts the usual GVF field with the upper white arrow pointing to the internal contour local minimum and the lower to the external ones. (d) displays the GVF force field computed by the modified edge map only containing the external contour local minimum directed by the arrow. The new GVF force field could reactivates the resultant internal contour forward to the external contour. Endocardium and epicardium are located in a single snake evolution procedure successively.

![Figure 3. Edge map \( f_{\rho} \) and GVF force field.](image)

### 4. Experiments on in vivo Data

In the following experiments, we will test the proposed methods and show the effectiveness of them. Firstly with the circumferential sample frequency \( T = 270 \), the image data are transformed to polar coordinates. On account of that the endocardium and epicardium are not close in the transform images, it is necessary to add an additional constraint to ensure the superposition of the contour beginner and the end. Here the strategy adopted is to copy the first column to the right side of the image matrix and keep the snake elements on the two columns consistent and differentiable during the whole evolution.

Taking the image in Fig.2 as an example, Fig.3(c) draws its external force field which is disturbed by papillary muscle, weak boundaries and noise. Without global constraint, the external force field pulls the snake to a false contour shown in Fig. 4(a). This result is hardly to accept. Fig. 4(b) illustrates the internal contour locating with the proposed line constraint pushing the snake to the desire solution. The new constraint overcomes the papillary muscle and noise, and prevents the snake contour from leaking out from weak boundaries. After the endocardium is located, we modify the edge map as mentioned in Section 3.4 and use it to compute a new GVF external force for epicardium extraction. Fig.3 (b) and (d) are the modified edge map in direction of \( \rho \) and the new GVF field respectively. Taking the resultant endocardium as initialization, the new GVF force field reactivates the snake to evolve further to epicardium. Also the global constraint behaves perfect again to conquer the weak boundaries. In the end, the segmentation results are converted to Cartesian coordinates shown in the third row and the third column of Fig5.

![Figure 4. Segmentation of endocardium and epicardium with and without line-like constraints.](image)

Fig.5 demonstrates the segmentation result that applying the proposed method on one slice of in vivo data. From the images we can see that the method overcomes noise and weak boundaries perfectly either on endocardial and epicardial contours. While in some images, the papillary muscle still affects the internal contour extraction because endocardial contour in the transform image is too curvy to fit the line-like constraint. This could be improved by putting the origin close to the papillary muscle or setting different weights \( \eta \) for different part of endocardium. In general,
the segmentation results of the LV are satisfactory. The parameters for model are $\alpha = 1, \beta = 1, \gamma = 1, \eta = 0.3$.

Figure 5. Segmentation of the left ventricle.

5. Conclusions

In this paper, we propose a novel strategy, radial GVF snake, for segmentation of left ventricle from cardiac MR images. The contributions of our work include: (1) automatic localization of the left ventricle, (2) tracing the snake elements in the transform image along 1D radial direction rather than 2D image plane and simplifying the snake internal energy to 1D, (3) adopting a line-like shape energy to conquer papillary muscle, noise and weak boundaries, (4) modification of GVF external force to extract epicardium and accomplishing the LV segmentation in a single snake evolution. Experiments on in vivo data approve that our algorithm could conquer noise and weak boundaries perfectly and segment the LV effectively when the contour shape is more close to a straight line in the transform image. For further study, we look forward to automatically find proper weights for different parts of LV to overcome papillary muscle better.

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7. References