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Automatic Left Ventricle Segmentation using Split Energy Function including Orientation Term from CTA

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Abstract

In this paper, we propose an automatic left ventricle segmentation method in computed tomography angiography (CTA) using separating energy function. First, we smooth the images by applying anisotropic diffusion filter to remove noise. Secondly, the volume of interest (VOI) is detected by using k-means clustering. Thirdly, we divide the left and right heart with split energy function. Finally, we extract only left ventricle from left and right heart with optimizing cost function including orientation term.

Keywords: *image segmentation; left ventricle segmentation; cardiac CTA; image processing; split energy function, cost function optimization, orientation term.*

1. Introduction

Image segmentation is to extract specific region from the image. There are two methods of segmentation, top-bottom and bottom-up approach. Top-bottom is to divide the whole image to the part, and bottom-up is to detect regions from the part to the whole region. In the field of medicine, it is necessary to detect some organs or tumors from medical images for diagnosis. Computed tomography (CT) is an imaging procedure that uses x-ray technology to produce tomographic images of specific object. CT distinguishes bones better than organic tissues. The muscle and the cavities of the specific organ are not well differentiated, both appearing on close gray tones on the CT scan. CTA, CT angiography and one of medical images which have the information of the heart, is widely used in image segmentation [1] because it provides more detailed anatomic information about the organ. The disorders of the heart of blood vessels often cause cardiovascular diseases [2], and heart segmentation from CTA has been used for cardiac diagnosis. Several approaches for the automatic heart segmentation have been proposed. Olivier et al. [3] presented a heart segmentation method using an iterative Chan-Vese algorithm [4]. They used L1 fidelity term for the computational efficiency instead of L2 fidelity which is classic term. However, this approach extracted only the whole heart, so it is difficult to extract only left ventricle from CTA. Ecabert et al. [5] proposed automatic segmentation of four chambers by using statistical geometry model and training meshes from cardiac CTA images. This

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method required well-defined training data sets, too much time and effort to generate a template mesh. In this paper, we propose an automatic method to extract the left ventricle in CTA using k-means clustering [6] and split energy function which we develop without any training data sets and template meshes.

The remainder of the paper is organized as follows. The next section describes the proposed method of automatic segmentation of the left ventricle in cardiac CTA. This procedure consists of four processing steps. Section III presents the results of the proposed method to clinical dataset. In section IV, we summarize the results and discussion.

2. Method

A. Pre-processing

First, we remove the noise of the input CTA. In general, there is much noise in the cardiac CTA and it would not be vivid. So image smoothing is essential to segment heart region. There are many denosing methods which is to remove or reduce noise in images, Gaussian filtering, median filtering, bilateral filtering, anisotropic diffusion filtering [7] and so on [8]. Among them, we use anisotropic diffusion filtering [7], minimizes total variation (TV), to preserve the edge while smoothing the original image and preserves finer detailed structures in images. The equation of anisotropic diffusion filter is as follows [7].

$$\min \ TV = \int_{\Omega} \sqrt{u_x^2 + u_y^2}\, dxdy \quad , \tag{1}$$

where u is an image, u_x and u_y is the derivative of u with respect to x and y. To discretize and optimize this equation, Rudin et al. [9] proposed a method to minimize using gradient descent PDE. Through calculus of variations, the gradient descent PDE of the minimization is as follows.

$$\begin{cases} \partial_t u = \operatorname{div} \frac{\nabla u}{|\nabla u|} + \lambda(f-u), \\ \nu \cdot \nabla u = 0 \quad \text{on } \partial\Omega. \end{cases} \tag{2}$$

Since this equation is convex, the steady state solution of the gradient descent is the global optimum. And gradient descent is performed by iterating equation (3).

$$\begin{aligned} u_{i,j}^{n+1} = u_{i,j}^n + dt\Big[\nabla_x^-\Big(\frac{\nabla_x^+ u_{i,j}^n}{\sqrt{(\nabla_x^+ u_{i,j}^n)^2 + (m(\nabla_y^+ u_{i,j}^n, \nabla_y^- u_{i,j}^n))^2}}\Big) \\ + \nabla_y^-\Big(\frac{\nabla_y^+ u_{i,j}^n}{\sqrt{(\nabla_y^+ u_{i,j}^n)^2 + (m(\nabla_x^+ u_{i,j}^n, \nabla_x^- u_{i,j}^n))^2}}\Big)\Big] + dt\lambda(f_{i,j} - u_{i,j}^n), \quad i,j = 1,\ldots,N-1 \end{aligned} \tag{3}$$

B. Extracting the Whole Heart

This step extracts the whole heart including the left and right heart region using thresholding and k-means clustering. And we expand the heart region by comparing the mean CT value of each cluster. So the clusters are removed as cardiac muscles and the other clusters are merged. To increase accuracy, we apply morphology operation, i.e. open operation which is to apply erosion and dilation [8]. (see Figure 1).

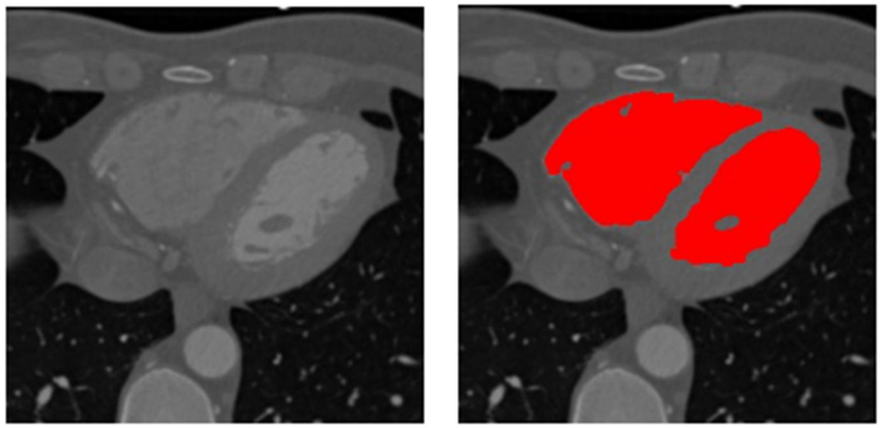

Figure 1. The result of the whole heart extraction. The input image of CTA(left) and the result of segmentation(right).

C. Separating the left and right heart from the Whole Heart

In this step, we split the heart into the left and the right heart from the clustered mask volume, the output of the previous extracting the heart region step. It is difficult to extract the left and the right heart automatically, because they are distinguished by ambiguous boundary. So we minimize the separating energy function for splitting the heart into the left and right heart. We propose the split energy function as follows.

$$E = \alpha \cdot Area\ term + \beta \cdot Intensity\ term + \gamma \cdot Orientation\ term \quad (4)$$

where α, β and γ is weights of the area, intensity and orientation term respectively, the area term is the area of intersection with the separating plane and heart region, and the intensity term is the bright value of the intersection plane.

$$Area\ Energy = \int_{\Omega_M} H(\text{mask(x)})\, dx, \quad where\ \ H(t) = \begin{cases} 1, & t \neq 0 \\ 0, & otherwise \end{cases}, \quad (5)$$

where mask(x) is the function of mask function from the heart extraction, and H(t) is the binary function w.r.t t value.

$$IntensityEnergy = the\ \ mean\ \ value\ \ of\ \ bright\ \ values\ in\ \ the\ \ heart\ \ region \quad (6)$$

The orientation term is the direction of the heart which is calculated by PCA [10, 11].

$$Orientation\ Energy = 1 - <1^{st}\ Eigen\ vector,\ OV> \quad (7)$$

where OV is the vector of hear orientation and the notation < , > means dot product. When the Eigen vector and OV is the same direction, the orientation term is zero, because if the Eigen vector and OV are the same, the dot product of them is 1. So the orientation energy is 1 – 1 = 0. To split the heart into left and right heart, we minimize the separating energy function E. We obtain the minimum by calculating using Powell's method [12]. Figure 2 shows that the process of the optimization for separating the heart into left and right using separating energy function and Powell's method. The position and orientation of the separating plane is detected using iterative optimizing process.

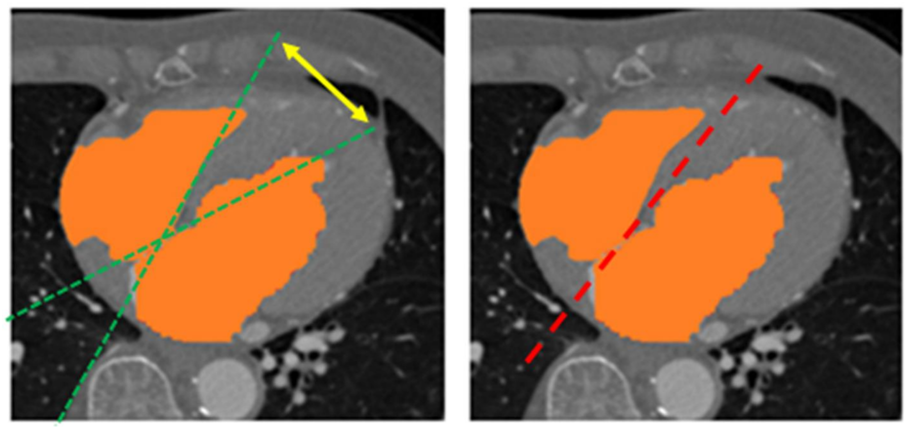

Figure 2. The detection of the separating plane for the left and right heart. The whole heart image and mask (left, the green dotted lines are candidates of the separating plane) and the result of the optimization (right, the red dotted line is the separating plane).

D. Remove right heart and leave left ventricle

In this step, we remove the right heart, i.e. right ventricle and atrium. In previous step, we divide left and right heart, so we only check the y-position of two heart, left and right heart. The upper heart is the right heart and the lower one is the left ventricle.

3. Experiments and results

We tested our method using the system which has the Intel® Core™2 Quad 3.4 GHz processor, 16 GB of main memory and Windows 10. We extract the left and right heart from ten CT images and they were obtained from a different patient. The numbers of images per scan ranged from 192 to 227. Each image had a matrix size of 512 × 512. The voxel size was 0.36. Figure 3 shows the result of the left/right heart and left ventricle segmentation. Table 1 shows the computational time for each step. For the evaluation of the computational performance of the proposed method, we measured the total processing time. The average of total processing time, from first step to third step, was 15.43 ± 1.29 s. In figure 3, the area of blue is the region of right heart, and the area of red is the region of left heart. In addition, we extract an iso-surface from the result of the segmentation and rendered it (see Figure 3 and 4).

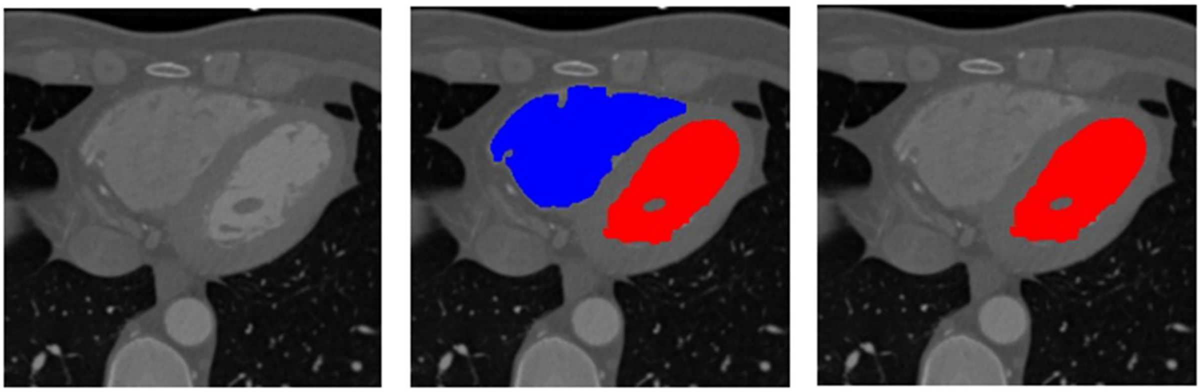

Figure 3. The result of the left and right heart and left ventricle segmentation. The input image of CTA (left), the result of heart division (middle) and the result of left ventricle segmentation

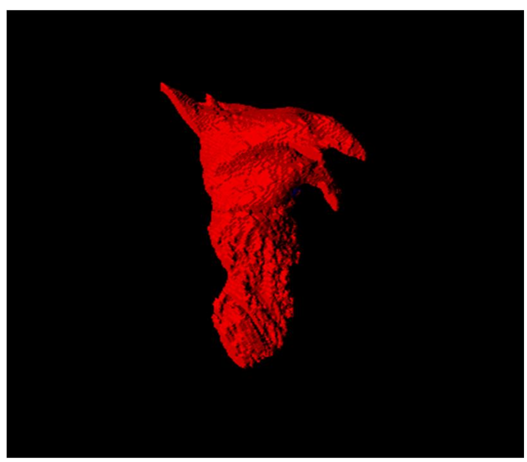

Figure 4. The iso-surface extraction of left ventricle

Table 1. Computational Time for Each Segmentation Step(sec)

Data	Smoothing image	Extracting heart	Separating heart	Leaving left ventricle	Total
1	5.5	1.7	6.4	0.1	13.7
2	6.2	2.1	7.8	0.2	16.3
3	5.7	1.6	6.6	0.1	14.0
4	7.1	2.3	7.5	0.2	17.1
5	6.1	1.9	7.1	0.1	15.2
6	7.5	2.7	6.9	0.1	17.2
7	5.3	2.1	6.5	0.1	14.0
8	6.7	2.0	6.4	0.1	15.2
9	7.3	2.5	7.0	0.1	16.9
10	6.2	1.5	6.9	0.1	14.7

4. Conclusion

It is difficult to segment the heart, especially left ventricle, because the chambers of the heart have weak edge or no edge. This paper presented a segmentation method of the left ventricle region using the optimization of split energy function including orientation term. This method is expected to be used in cardiac diagnosis.

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