Automatic Segmentation and Reconstruction of Coronary Arteries Based on Sphere Model and Hessian Matrix using CCTA Images

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Abstract. Cardiovascular disease (CVD) is the most common cause of death in the world. Accurate coronary arteries segmentation is the basis for heart disease diagnose. But in coronary computed tomography angiography (CCTA) images, the complex structure of coronary vessels and the low contrast of thin vessels cause difficulty in coronary arteries segmentation. In this paper, an automatic segmentation algorithm is proposed to extract vessels from CCTA. Firstly, the hessian matrix is used to enhance vessels in CCTA images, and then, the moving sphere model we proposed is used to extract centerline of coronary arteries. Experimental results showed that the proposed model provides good-quality segmentation.

1. Introduction

1.1. Backgrounds
Cardiovascular disease is the leading cause of death in the world[1]. Coronary computed tomography angiography (CCTA) as a non-invasion imaging modality is a common method for diagnosis of heart disease[2]. Accurate segmentation and visualization of the coronary arteries play an important role in clinical diagnosis of heart disease. However, the exciting coronary artery segmentation algorithm usually has low accuracy and is not automated. Then most clinicians still mainly rely on manual operations.

Two kinds of problems occur in the segmentation of the coronary vessel structure: (1) the morphology and structure of coronary vessels are complex, and vary greatly among individuals. (2) The intensity of the coronary vessels has similar to peripheral tissues, such as atrium and ventricle[3].

1.2. Existing method of vessel segmentation
Segmentation is a key step toward accurate visualization, diagnosis, and quantification of vascular pathologies. Various methods have been proposed to segment vessels from medical images in the previous literature. These methods are roughly categorized as region-growing method, active contour models, statistical models and centerline method[4].
The region growing method needs to select one or more seed points, and gradually adds the voxels to the growth region by examining whether neighboring pixels of seed points conform to a predefined growth standard. The method is simple and fast, but the growth conditions and seed points need to be manually specified. Yang and Cai combine morphological method and region growing method to segment cardiac cavity and coronary artery from CCTA data [5,6]. Metz et al. add branch and leak detection to region growing method to extract three main branches of coronary artery, but small branches are still not taken into account[7].

Active contour model requires the evolution of curves driven by different forces. The initial contour of deformable models must be near to the target, and the parameters are complex [8]. Yang et al. improve level set algorithm by adding statistical information to extract main branches of the left coronary artery, the left anterior descending branch, the left circumflex branch and the right coronary artery[9]. Hernandez and Frangi join the distribution of vascular geometric feature estimated by k-nearest neighbor nonparametric estimation method in an energy function to solve the uneven distribution of grayscale in vascular tissue[10].

Recently, the statistical methods have received considerable attention, but it is difficult to deal with classes of overlapped intensities. Lacoste et al. propose a method to segment coronary arteries in 2D images using Markov markers and obtain good results[11].

Efforts were made to combine the aforementioned method to form the hybrid methods. Some methods in the existing literature can effectively segment 2-D images. However, these techniques are unsuitable for 3-D segmentation because the model is complex and the speed is slow[12].

2. METHOD
To segment coronary artery from CCTA data accurately, A mixture algorithm with sphere model and multi-scale filtering is proposed. To enhance the vessel, Multi–scale filtering is used to obtain lumen structures. The flow chart of the proposed method is given in Fig.1, followed by a brief explanation.

![Fig.1 the framework of the proposed method.](image)

2.1. Enhancement algorithm
Hessian matrix is used to enhance lumen structures as the shape of the coronary arteries is approximately tubular. For a 3-D image, the Hessian of an image \(I(x,y,z)\) at \((x,y,z)\) is given by Equation(1):

\[
H(I(x,y,z)) = \begin{bmatrix}
\frac{\partial^2 I}{\partial x^2} & \frac{\partial^2 I}{\partial x \partial y} & \frac{\partial^2 I}{\partial x \partial z} \\
\frac{\partial^2 I}{\partial y \partial x} & \frac{\partial^2 I}{\partial y^2} & \frac{\partial^2 I}{\partial y \partial z} \\
\frac{\partial^2 I}{\partial z \partial x} & \frac{\partial^2 I}{\partial z \partial y} & \frac{\partial^2 I}{\partial z^2}
\end{bmatrix}
\] (1)

The eigenvalues of the Hessian matrix are \(\lambda_1, \lambda_2,\) and \(\lambda_3\). Frangi proposed Equation(2) to define a vesselness function[13].

\[
v_v(\lambda) = \begin{cases} 
0, & \text{if } \lambda_1 > 0 \text{ or } \lambda_2 > 0 \\
(1 - \exp(-R_w^2/2\alpha^2))\exp(-R_s^2/2\beta^2)(1 - \exp(-S^2/2\epsilon^2)) & \text{otherwise}
\end{cases}
\] (2)

The measure provide response at different scales since vessels appear in different sizes. The differentiation of Hessian matrix is defined as a convolution with derivatives of \(\delta\)-dimension Gaussians as equation (3) [13].
The measure in equation (4) is analyzed at different scales $\delta$. 

$$v_{0} = \max_{\delta_{\min} \leq \delta \leq \delta_{\max}} v_{0}(\delta, \lambda)$$

(4)

To enhance both main and thin vessels, the filtering scale is set to [4 14].

2.2. Moving sphere model

The human vascular system is an elastic and expansive pipeline system. The cross-section of a vessel is closed curve and approximately circular. A moving sphere model is established, and the sphere rolls along the vessel are illustrated in Fig.2. The central axis of the ball is the central axis of the vessel, and the diameter of the ball is the diameter of the vessel [14].

![Fig.2 Searching sphere center in 3D vessel.](image)

Whether the sphere center $O$ and the radius $r$ satisfy the consistent conditions of the sphere as it moves should be determined. The current sphere will be the next moving sphere if the ratio of the gray value of points in the circle to the total number of points in the circle is higher than the predetermined threshold. The threshold value is set between 90% and 95% by experience [15].

3. Validation

The experimental data are obtained from the General Hospital of Guangzhou Military Command of PLA, and the imaging device is a dual-energy CT (Somatom Definition, Siemens). The volume of data is $512 \times 512 \times 411$. The proposed algorithm is implemented using Matlab 2016a on a PC with Intel Core™ i5, CPU 1.8 GHz, and 8G-DDR-RAM.

As shown in Fig.3, the images are original slices of the CCTA data. The row points to the location to be divided which is coronary arteries.

![Fig.3 Three slices of the CCTA images. (The arrow points to the coronary artery.)](image)

Fig.4 is the result of coronary artery segmentation and three-dimensional reconstruction. Fig.4(a) shows the centerline extraction of the LM coronary artery, the left anterior descending coronary artery, and the left circumflex coronary artery. Fig.3(b) shows the measurement of the inner diameter. Moreover, coronary artery stenosis with only 2 pixels wide still presents no fracture, and significant bifurcation is observed. Clinicians can directly determine the stenosis degree and branch distribution of the coronary artery, which can improve the quality of CVD diagnosis [6,14-15].
Fig.4  (a) Centerline result of coronary artery. (b) Inner diameter of coronary artery.

4. Conclusion

A novel method we proposed to segment coronary artery and extract its centerline automatically, with consideration of the gray and structural features of blood vessels. Firstly, Hessian Matrix is used to enhance images. Then, a moving sphere model is constructed to segment coronary arteries. The novel method displays high accuracy, and it can be applied to CCTA images well.

In future work, we will solve the detection of coronary artery stenosis and calcified plaque automatically to assist doctors in the implementation of reasonable cardiovascular disease auxiliary diagnosis and cardiac surgery planning.

Acknowledgments

This work was financially supported by Guangdong Province Youth Innovation Talent Project (No.2015KQNCX071), Guangdong Pharmaceutical University innovation and strong school project(No.2015cxqx169).

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