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MULTISCALE VESSEL FILTERING IN ASSISTING THE GENERATION OF PATIENT-SPECIFIC CFD MODELS FOR CORONARY ARTERIES

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INTRODUCTION

Imaging based computational fluid dynamics (CFD) simulation of hemodynamics has become an active research topic in the past few decades [1, 2]. Realistic and patient-specific models of important blood vessels such as carotid arteries and coronary arteries can be obtained through *in-vivo* imaging techniques, such as MRI and CT angiography. Based on these models, local features of hemodynamics in individual patients can be further acquired using CFD simulations. The velocity and wall shear stress (WSS) distributions inside the vessel lumen may give valuable information on the formation and progression of atherosclerosis.

Building the CFD vessel models from 3D images, however, remains a challenging task, because vessels are long and thin anatomical structures with complex shapes and curvatures, and general image segmentation algorithms usually do not work well on vessels. More challenges lie in the problem of segmenting coronary arteries from CTA images. As shown in Figure 1 (a), coronary arteries share the same intensity values with other blood-filled regions in the image, and the left coronary arteries are surrounded by these regions so that in the MIP (maximum intensity projection) image shown in Figure 1 (b), the left coronary arteries can hardly be observed. It can be easily predicted that a simple iso-surface or pixel classification would include not only the coronary arteries, but other big blood-filled regions as well. In order to extract coronary arteries from the volumetric data, we propose to apply a three-dimensional multi-scale line filter [3, 4] to the image volume of interest (VOI) and isolate the coronary arteries from the filter response.

METHODS

The methods employed in this work are based on the analysis of the eigenvalues of the Hessian matrix of a 3-D image.

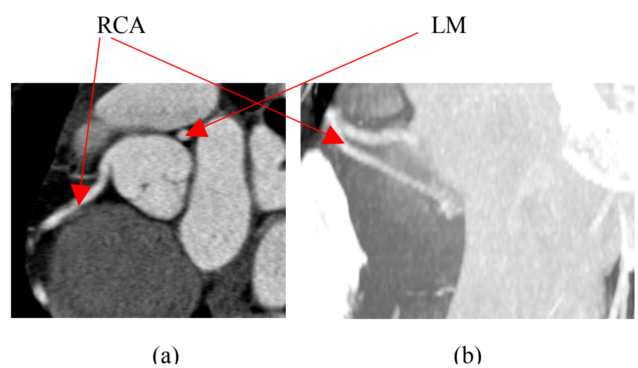

Figure 1. (a) A single slice of the CTA volume; (b) MIP of the CTA volume.

The Hessian matrix of a pixel I(x) at location x = (x,y,z) can be written as:

$$\nabla^2 I(x) = \begin{bmatrix} I_{xx}(x) & I_{xy}(x) & I_{xz}(x) \\ I_{yx}(x) & I_{yy}(x) & I_{yz}(x) \\ I_{zx}(x) & I_{zy}(x) & I_{zz}(x) \end{bmatrix} \tag{1}$$

The elements of the Hessian matrix can be calculated by convolving the image with the second partial derivatives of an isotropic Gaussian function with standard deviation σ:

$$I_{uv}(x;\sigma) = \left(\frac{\partial^2}{\partial u \partial v} G(x;\sigma) \right) * I(x) , \tag{2}$$

where u, v denotes x, y or z.

The properties of the eigenvalues ($|\lambda_1| \le |\lambda_2| \le |\lambda_3|$) of the Hessian matrix give important information about the type of structures the current pixel belongs to. The following condition indicates the pixel belongs to a tubular-like structure, which is the vessel-like structure in our imagery:

$$\begin{cases} 0 \approx |\lambda_1| << |\lambda_2| \leq |\lambda_3| \\ \lambda_2 < 0, \lambda_3 < 0 \end{cases} \tag{3}$$

In order to discriminate the vessel-like structure from the plate-like and the blob-like structure, we adopted the vesselness measure proposed by Frangi, *et al*. [4]:

$$M(x;\sigma) = \begin{cases} 0, \quad if \quad \lambda_2 > 0 \quad or \quad \lambda_3 > 0 \\ \left(1 - \exp\left(-\frac{R_A^{\ 2}}{2\alpha^2}\right)\right)\exp\left(-\frac{R_B^{\ 2}}{2\beta^2}\right)\left(1 - \exp\left(-\frac{S^2}{2c^2}\right)\right), o.w. \end{cases}, \tag{4}$$

where $R_A = \frac{|\lambda_2|}{|\lambda_3|}$, $R_B = \frac{|\lambda_1|}{\sqrt{|\lambda_2 \lambda_3|}}$, $S = \sqrt{\sum_{1 \leq i \leq 3} \lambda_i^2}$.

α, β and c are constants that control the balance between the three terms.

The vesselness measure in Equ. (4) can be obtained at different scales by using several different values of σ. The final multi-scale vesselness measure is achieved by selecting the largest value of the measure at different scales:

$$M_{multi}(x) = \max_{\sigma} M(x;\sigma) \tag{5}$$

Vessel-like structures can then be extracted by acquiring the iso-surface of the vesselness measure $M_{multi}(x)$.

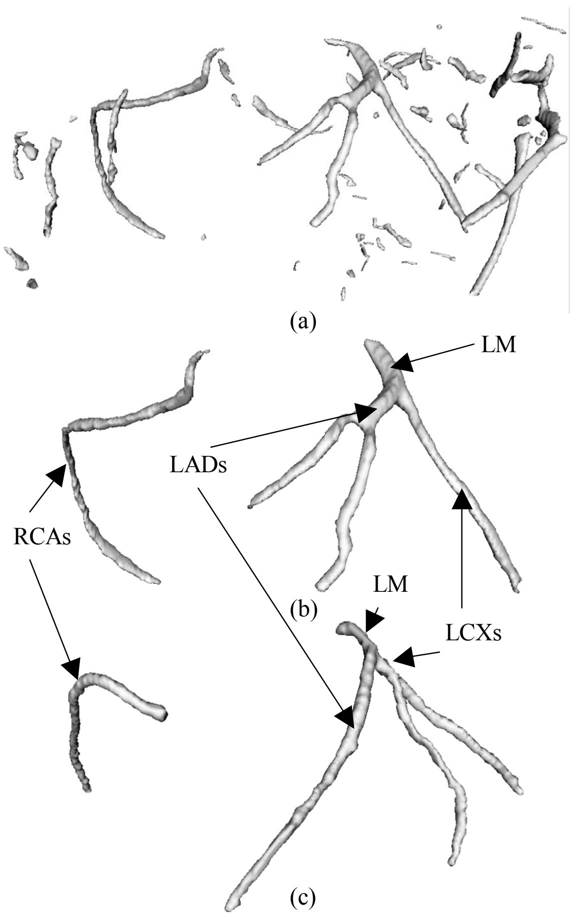

Figure 2. (a) Vessel filter response of the 3D volume within FOI; (b) Results after cleaning up (a); (c) A second example of the extracted coronary arteries.

RESULTS

We applied the proposed method to 8 volumetric CTA datasets, including healthy volunteers and patients with different degrees of coronary artery diseases. The filter response successfully extracted all major coronary arteries (LM, LAD, LCX, and RCA) in the 8 datasets and in several cases, more branches of LAD and LCX are also extracted.

The direct filter response includes some vessel-like structures other than the coronary arteries, as shown in Figure 2 (a). In order to isolate the coronaries, we perform a further clean-up step by selecting the longest connected vessels starting from a seed point placed at the root of the left and right coronary trees. Figure 2 (b) shows the result after the performing the clean-up step on (a). Figure 2 (c) shows the result from another dataset. Major coronary arteries are labeled in the figures.

DISCUSSION

In this work we presented an approach to isolate coronary arteries from 3D volumetric CTA data based on a vesselness measure derived from the eigenvalues of Hessian matrices of the image. This method efficiently and effectively isolates vessel-like structures from the 3D data. The resulting surfaces, however, may not be smooth enough yet for the CFD simulation to be directly applied on. It is suggested that they serve as an initialization for more sophisticated image segmentation and surface construction algorithms [5] to refine the model in order to meet the requirements of CFD models. We also observed disconnected vessels in a few cases where there are calcium deposits or severe narrowing of the coronary arteries due to atherosclerotic plaques. At this point we track down the coronary tree by starting a new seed point at the broken site, and a more automatic approach is being developed. The discontinuity may also be removed by evolving the surface using the level set methods [6] that allow topological changes in the shape, if the vessel is connected in the original image.

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