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3D reconstruction of coronary arteries and atherosclerotic plaques based on computed tomography angiography images

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ABSTRACT

The purpose of this study is to present a new semi-automated methodology for three-dimensional (3D) reconstruction of coronary arteries and their plaque morphology using Computed Tomography Angiography (CTA) images. The methodology is summarized in seven stages: pre-processing of the acquired CTA images, extraction of the vessel tree centerline, estimation of a weight function for lumen, outer wall and calcified plaque, lumen segmentation, outer wall segmentation, plaque detection, and finally 3D surfaces construction. The methodology was evaluated using both expert's manual annotations and estimations of a recently presented Intravascular Ultrasound (IVUS) reconstruction method. As far as the manual annotation validation process is concerned, the mean value of the comparison metrics for the 3D segmentation were 0.749 and 1.746 for the Dice coefficient and Hausdorff distance, respectively. On the other hand, the correlation coefficients for the degree of stenosis 1, the degree of stenosis 2, the plaque burden, the minimal lumen area and the minimal lumen diameter, when comparing the derived from the proposed methodology 3D models with the IVUS reconstructed models, were 0.79, 0.77, 0.75, 0.85, 0.81, respectively. The proposed methodology is an innovative approach for reconstruction of coronary arteries, since it provides 3D models of the lumen, the outer wall and the CP plaques, using the minimal user interaction. Its first implementation demonstrated that it provides an accurate reconstruction of coronary arteries and thus, it may have a wide clinical applicability.

1. Introduction

Coronary Artery Disease (CAD), in which atheromatic plaques build up inside the coronary arteries, is the most common type of heart disease and is considered as the leading cause of morbidity and mortality world wide [1]. Non-invasive cardiovascular imaging and particularly Computed Tomography Angiography (CTA) has experienced a remarkable progress in the last years [2,3]. CTA has been gaining widespread acceptance in clinical practice for the investigation of suspected CAD, since it is able to visualize the coronary arteries and their anatomy and allows the interpreter to evaluate the presence, extent and type (calcified (CP) or non-calcified (NCP)) of atherosclerotic plaques [4], without the invasive catheterization procedure.

Different studies have indicated that CTA modality is able to analyze accurately the coronary artery remodeling and provides not

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only the detection and quantification of the atherosclerotic plaque [5,6], but also the classification of its composition [7]. In addition to its high accuracy, CTA provides robust prognostic information in patients with suspected CAD and allows the risk stratification as well, when CAD is present [8] while it can be used for prediction of plaque growth based on computational modelling [9,10]. Existing studies have demonstrated that CTA derived measures, such as the number of vessels with significant stenosis, the luminal stenosis, the stenosis location, the plaque burden and the composition of the plaque contribute to diagnostic and prognostic abilities of coronary CTA [11,12].

An accurate 3D model of coronary arteries, except for visualizing the vessel geometry and its plaque distribution, allows also the blood flow simulation and the investigation of the role of biomechanical factors, such as static pressure, wall shear stress, blood viscosity on the localization and progression of atherosclerosis [13]. In addition to this, a 3D coronary imaging has the potential to provide a more comprehensive evaluation of the risk for CAD progression [14].

In the literature, different studies have been presented to determine the accuracy of 3D artery reconstruction and the assessment of plaque using CTA. Voros et al. [15] presented a study for the evaluation of 3D quantitative measurements of coronary plaque by CTA using Intravascuar Ultrasound (IVUS). Another similar approach was introduced by Graaf et al. [16], who studied the correlation between the metrics derived by CTA automatic software (QAngio CT 1.1, Medis medical imaging systems) and those provided by Virtual Histology IVUS (VH-IVUS), which was defined as the gold standard. Arbab et al. [17] performed a study for the quantification of coronary arterial stenosis using CTA and demonstrated that CTA in comparison with the conventional angiography, is able to identify non-invasively patients with CAD. Athanasiou et al. [18] presented a semi-automated methodology for 3D reconstruction of arteries and their plaque morphology using CTA images and compared their approach using IVUS findings.

In this work, we present a new semi-automated methodology for 3D coronary artery reconstruction and plaque detection using CTA modality. In order to investigate the accuracy of our approach, we implemented two different validation approaches, using both expert's annotations and estimation of an IVUS reconstruction methodology. The comparison results indicated good agreement. The main innovative aspect of the presented methodology is its ability to reconstruct both the lumen, the outer wall and the CP plaques with the minimal user interaction. Furthermore, the proposed methodology incorporates a centerline extraction, using a minimum cost path approach. Thus, a successful and accurate centerline detection is guaranteed and the subsequent step of lumen segmentation is improved. In addition to this, it indicates a user friendly applicability, since the main user interaction is the detection of the start and the end point of each branch.

2. Materials and methods

The proposed methodology includes 7 stages. In the first stage, the acquired CTA images are pre-processed to detect vessel silhouette. In the second stage, a centerline extraction approach of the vessel is applied. In the third stage, a weight function for the lumen, the outer wall and the CP plaques is estimated. In the fourth stage, an extension of active contour models for lumen segmentation is implemented. In the fifth and sixth stage, similarly to the previous stage, a level set methodology for outer wall segmentation and plaque segmentation, respectively, is applied. Finally, in the last stage the 3D surfaces for the lumen, the outer wall and the CP plaques are constructed. In Fig. 1, the stages of the proposed methodology are shown.

2.1. Preprocessing

The image preprocessing step is applied in the axial DICOM acquired images to remove irrelevant details of the CTA images. A vessel enhancement filter, the Frangi Vesselness filter [19] is implemented to identify tubular structures and limit the region of interest (ROI) to vessel candidate regions. In Fig. 2, an example of the implementation of the Vesselness filter is shown.

2.2. Centerline extraction

The centerline is mainly required for creating an initial vessel mask for the vessel segmentation algorithm. However, the centerline extraction stage still remains a challenging task, since the size of the vessels is small and several reconstruction artifacts are observed. In the proposed methodology, a minimum cost path approach is implemented for the centerline extraction, based on Metzt et al. [20] approach.

The proposed centerline extraction methodology is quite simple and, therefore easy to implement, since the main requirement is the starting point and the ending point of the vessel to extract the corresponding centerline. The cost function, which is considered for the minimum cost path approach is a combination of the lumen and vessel weight.

Firstly, we extract the image weight based on the vesselness measure (w_{vessel}) [19]. Subsequently, we compute the value of the top 50% of the image intensities, which are larger than 100 Hounsfield Units (HU), considering only the parts of the image, where the w_{vessel} measure is larger than 0. This computed value *ml* is very significant, since it is used for the extraction of the lumen weight. More specifically, the lumen weight is extracted by using a generalized bell-shaped membership function and it is defined as:

$$w_{lumen} = 0.9 \cdot \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}} + 0.1, \tag{1}$$

where $a = 0.02$, b is the minimum value between $ml - l_{thres}$ and 500, and c is the value of $ml + cp_{thres}$. Heuristically, and making several experiments, the threshold of the lumen (l_{thres}) and the calcified plaques (cp_{thres}) was defined 80 HU and 400 HU, respectively. More details can be found in the Appendix.

The considered cost function V for the minimum path approach is a combination of the vessel and the lumen weight and is defined by:

$$V = w_{vessel} \cdot w_{lumen}. \tag{2}$$

In order to calculate the shortest distance from a list of points to all other pixels in an image volume, a Multistencil Fast Marching Method (MSFM) is implemented based on the approach described in [21]. An example of the above procedure is depicted in Fig. 3.

2.3. Estimation of weight function for lumen, outer wall and calcified plaque

Similar to the previous step, in this stage three different membership functions for the lumen, the outer wall and the CP plaques are computed, aiming to compensate different protocols for discriminating the lumen, the outer wall and the calcified plaque. These membership functions are all adapted to the mean vessel intensity across the centerline, assuming that this corresponds to the mean lumen intensity. More specifically, the mean lumen intensity $\bar{I}_{lumen}$ is calculated, taking into consideration only the pixels of the image, whose intensities are higher than 100 HU and their Euclidean distance from the extracted centerline is less than 5.

For the lumen a generalized bell-shaped membership function is used, whereas for the outer wall and the calcified plaque two