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Automated coronary artery tree segmentation in X-ray angiography using improved Hessian based enhancement and statistical region merging

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ABSTRACT

Background and Objective: Coronary artery segmentation is a fundamental step for a computer-aided diagnosis system to be developed to assist cardiothoracic radiologists in detecting coronary artery diseases. Manual delineation of the vasculature becomes tedious or even impossible with a large number of images acquired in the daily life clinic. A new computerized image-based segmentation method is presented for automatically extracting coronary arteries from angiography images.
Methods: A combination of a multiscale-based adaptive Hessian-based enhancement method and a statistical region merging technique provides a simple and effective way to improve the complex vessel structures as well as thin vessel delineation which often missed by other segmentation methods. The methodology was validated on 100 patients who underwent diagnostic coronary angiography. The segmentation performance was assessed via both qualitative and quantitative evaluations.
Results: Quantitative evaluation shows that our method is able to identify coronary artery trees with an accuracy of 93% and outperforms other segmentation methods in terms of two widely used segmentation metrics of mean absolute difference and dice similarity coefficient.
Conclusions: The comparison to the manual segmentations from three human observers suggests that the presented automated segmentation method is potential to be used in an image-based computerized analysis system for early detection of coronary artery disease.

1. Introduction

Coronary artery disease (CAD), also known as ischemic heart disease, is the most common type of cardiovascular diseases and the leading cause of death worldwide [1]. Morphological or anatomical information about the cardiovascular system is essential for diagnosing CAD and planning of surgical procedures or catheter interventions. In clinical practice, 2D X-ray coronary angiography remains an important diagnostic and therapeutic tool for cardiovascular diseases [2]. In traditional X-ray angiography, a radio-contrast agent is usually injected into the blood vessel by means of a catheter to make the blood flow visible for about 3–5 s and imaged using X-ray based techniques such as fluoroscopy. Correct assessment of coronary arteries reflected in coronary angiography images plays a significant role in a number of clinical procedures, such as measurement of vessel width, reflectivity, tortuosity, and abnormal branching, stenosis grading, navigation and localization of coronary stent, etc. However, because of the geometrical complexity and fine characteristics of detailed vascular structures, accurate visualization and quantification of blood vessels in coronary angiograms still remains a problem [3,4].

With the rapid development and progress in computing technology, image analysis algorithms that support automated medical diagnosis have been gaining importance [5]. As a fundamental step, vessel assessment demands the extraction of the coronary arteries from the background for various clinical purposes, such as detection of plaques [6,7], vessel diameter measurement to diagnose hypertension and cardiovascular diseases [8], and bypass surgery and coronary artery stenting [9]. Although it is possible for medical experts to delineate blood vessels on coronary angiography images, manual delineation of the vasculature becomes tedious or even impossible when the number of vessels in an image is large or when a large number of images is acquired [10]. Therefore, the develop-

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ment of fully automated vessel tree segmentation in angiograms is highly desirable.

Accurate vessel segmentation on angiography images is a challenging task for several reasons: (1) poor resolution; (2) noise degradation; (3) low contrast between the vessels and the background; (4) intensity inhomogeneity; (5) variability of the vessel width and length; (6) the bifurcations and crossings between vessels. Thus, it is difficult to perform an accurately automated vessel segmentation through traditional segmentation methods [11]. In order to achieve an accurate vessel tree extraction, the vessel enhancement procedure is an important preprocessing step. There are a variety of vessel enhancement methods in the literature [4,12–14]. Among them, linear or non-linear filtering-based approaches are popular in enhancing vessel structures. For instance, Poli and Valli [15] implemented a real-time enhancement and detection of blood vessels based on a set of linear filters, obtained as linear combinations of properly shifted Gaussian kernels, sensitive to vessels of different orientation and thickness. Lasso and Trucco [2] presented a vessel enhancement method using support vector machine (SVM) temporal filtering for X-ray angiographic images based on statistical learning. The SVM was utilized to learn the characteristics of the evolution of gray levels in time caused by the contrast media injection. These methods performed poorly when the images were affected by noise and were less efficient on the delineation of thin blood vessels. Krissian [16] performed an non-linear anisotropic diffusion to search for the local orientation of a vessel to perform anisotropic smoothing without blurring its edge, which effectively enabled enhancement of contours as well as diffusion along the contours. Manniesing et al. [9] introduced a vessel enhancing diffusion within the framework of scale space theory to combine a smooth vessel filter with a non-linear anisotropic diffusion scheme. The amount and orientation of diffusion depend on the local vessel likeliness. The main disadvantage of the non-linear filtering based methods is that they can hardly detect vessels in a wide range due to the fixed scale analysis [10].

Hessian-based multiscale enhancement methods have been widely used due to their ability to acquire both dimensional and directional information of vessels, in which Hessian matrix eigenvectors have relation with vascular structure. The conventional Hessian-based enhancement method [17–19] involved multiscale convolution by a Gaussian filter at multiple scales and Hessian eigenvalue analysis to determine the local shape of the structures (line-like or blob-like) on the pixel basis. The drawbacks of the Hessian-based approaches are that they are highly sensitive to noise due to the second-order derivatives and tend to suppress junctions since junctions are characterized as same as the blob-like structures. Junction suppression leads to the discontinuity of the vessel network and has adverse effects at coarse scales, yielding a blurring of the thin vessels that are well processed at fine scales. To overcome the above problems, Truc et al. [10] presented a vessel enhancement method for angiography images by incorporating the use of line-like directional features extracted by a directional filter bank, to obtain more precise Hessian analysis in noisy environment and thus can correctly reveal small and thin vessels, meanwhile it is able to avoid junction suppression, which in turn, yields continuous vessel tree. But, this type of methods generally led to an intensity inhomogeneity, especially in vessel junction regions. Xu et al. [20] further improved the Truc et al.'s method by computing vessel similarity metric as weights in the recombination of enhanced directional images to greatly retain sharp vessel edges, but lost the information at vessel crossings due to the intensity enhancement.

The main purpose of this work is to develop a computerized segmentation method to automatically extract artery trees on coronary angiography images. Researchers have approached this problem from many different angles, applying very different strategies. According to segmentation classification reported in [21,22], vessel segmentation algorithms are divided into three main categories: (1) pattern recognition (PR) techniques; (2) model-based approaches; (3) tracking-based approaches. PR methods are mainly concerned with automatic detection of vessel structures and vessel features, which include thresholding [5,23,24], region growing and merging [25,26], statistical modeling and matching filters [4,27–29], mathematical morphology [30,31], ridge-based approaches [32], and so on. Major of these methods focused on vessel segmentation for retinal images, which is less noisy compared to the coronary X-ray images. Model-based approaches are widely used segmentation methods to extract vasculature, which apply explicit vessel models, such as deformable models, parametric models, geometric model, etc., to detect vessel boundaries. For example, Sum and Cheung [33] introduced a level-set based active contour for vessel extraction by considering local image contrast in order to handle nonuniform illumination presented on clinical angiograms. Zhao et al. [34] integrated a region growing method and a region-based active contour model with level set implementation applied to segment retinal vessels. These methods are sensitive to the initialization of the contour and need to set controlling parameters manually. Li et al. [35] derived a classical level set method which regularized the level set function during evolution to eliminate the re-initialization procedure. Further, Liu et al. [11] presented a level set model combining with an adaptive mean shift clustering method, in which the results of mean shift clustering can automatically and speedily generate an initial contour of level set evolution. However, these methods suffered a boundary leakage problem and had a difficulty in handling vessel bifurcations. Tracking-based approaches are also popular in detecting and extracting vessels. Recently, Oliveira et al. [36] implemented a complete vascular network tracking using an optimization scheme to iteratively track the vessel structure by inherently handling bifurcations and paths. Zhou et al. [6] presented a segmentation and tracking algorithm for coronary arterial tree extraction based on a 3D dynamic balloon tracking method in coronary CT angiography scans. These methods also required initialization and were computationally expensive due to the iterative process.

On the other hand, supervised methods are adopted based on pixel classification, which consists on classifying each pixel into two classes of vessel and non-vessel. For instance, Marin et al. [37] employed a neural network scheme for blood vessel segmentation on retinal images and computed gray-level and moment invariant-based feature for pixel classification. Soares et al. [38] used a Gaussian mixture model based Bayesian classifier, and maximum Gabor transform response over angles at four different scales were considered as pixel features. Liskowski and Krawiec [39] recently trained a deep neural network on a large sample of retinal image and showed a good performance on detection of fine vessels. Although supervised methods have proved to be effective and have a high accuracy in detecting vessels, these methods require a training process which is computationally expensive.

In this work, we present an automated vessel tree segmentation method in coronary X-ray angiography using improved hessian based enhancement and statistical region merging approach. This method is simple and efficient in automatically identifying the vessels of interest by taking advantage of powerful image processing techniques. A schematic diagram of this proposed vessel segmentation method is shown in Fig. 1. First, the angiography image is denoised and corrected via a two-step preprocessing approach. A non-local (NL) means [40] is performed to eliminate image noise meanwhile preserving subtle vascular structure. A shade-correction method is used to reduce intensity variation in the background. A multiscale-based adaptive Hessian-based enhancement filter is applied to the shade-corrected images to improve the complex vessel structures as well as small vessel delineation. Finally, a simple sta-