Improvement of Hessian Based Vessel Segmentation Using two Stage Threshold and Morphological Image Recovering

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Abstract

In many of vessel segmentation methods, Hessian based vessel enhancement filter as an efficient step is employed. In this paper, for segmentation of vessels, HBVF method is the first step of the algorithm. Afterward, to remove non-vessels from image, a high level threshold is applied to the filtered image. Since, as a result of threshold some of weak vessels are removed, recovering of vessels using Hough transform and morphological operations is accomplished. Then, the yielded image is combined with a version of vesselness filtered image which is converted to a binary image using a low level threshold. As a consequence of image combination, most of vessels are detected. In the final step, to reduce the false positives, fine particles are removed from the result according to their size. Experiments indicate the promising results which demonstrate the efficiency of the proposed algorithm.

1. Introduction

In recent decades, medical imaging techniques such as computed tomography angiography (CTA) and X-ray angiography have aided the diagnosis of atherosclerosis to the highest degree. In this way, vessel analysis in medical images is one of the most significant research fields since it is applicable in diagnostic and intervention planning purposes. For various visualization applications such as endovascular views or multiplanar reformats, extraction of vessel centerline can be employed to generate specific visualization information. Also, for some of other applications including quantification, e.g. for stenosis grading, or to determine the dimension of stents, vessel segmentation can play an important role. In most of approaches, proposed in literature, for vessel analysis, images enhancement is the first step to improve vascular structures. It helps vessel visualization, e.g. in maximum intensity projections or volume rendering techniques. For vessel segmentation, in case of coronary arteries in angiographic images, digital post-processing operations are necessity to isolate vessels from background. In many of methods the knowledge that vessels are tubular structures is employed to describe vessels by their central axes and width.

Central vessel axis (CVA) segmentation is presented in [1, 2], in which to identify the type of local structure in image (e.g., tubular-like), information from 2nd-order derivatives at multiple scales is extracted. This information is obtained by inspecting the main mode of variation in Hessian matrix. Lorenz et al. [3], Sato et al. [4], and Frangi et al. [5] have proposed Hessian-based vessel enhancement filters (HBVF) as an applicable method to a variety of imaging tasks including DSA [3, 5], CTA [4], and 3D MRA [1, 4, and 5]. In [6], vessel enhancement is accomplished using vessel enhancing diffusion (VED) to improve visualization and diagnostic purposes.

In this approach, vessel segmentation in X-ray angiographic frame is accomplished using some experts which are in tandem. Firstly Hessian based vessel enhancement filter (HBVF) is applied to image and a primitive threshold is applied in it to remove non-vessel particles from image. Afterward, remaining parts of vessels in image are recovered and dilated by morphological operations, adjusted by Hough transform. Finally second threshold is applied to the Hessian based filtered image and its combination with recovered image is achieved to detect vessels of angiographic image. Remainder of the paper is as follows:

In section 2 vesselness filter for enhancing the tubular structures in image is introduced. Section 3 focuses on the proposed vessel segmentation method, followed by experimental results in section 4 and conclusion in section 5.
2. Vesselness filter

This filter aims to analysis eigensystem of the Hessian matrix to determine curvature direction of image which is necessity for detection of vascular structures. Curvature direction in each point is the direction according to eigenvector of Hessian matrix in which the second order of image information is extremum. For better understanding Hessian matrix which determines the second order information of 2D image is given as follows:

\[ I(x, y) \Rightarrow H = \begin{bmatrix} I_{xx} & I_{xy} \\ I_{yx} & I_{yy} \end{bmatrix} \]

Where \( I \) and \( H \) denote original image and Hessian matrix and \( I_{xx}, I_{yy}, I_{xy} \) and \( I_{yx} \) denote second derivative of image information, respectively. To obtain \( \frac{\partial I}{\partial x} \) and \( \frac{\partial I}{\partial y} \) original image can be filtered using [-1 2 -1] and \([-1 2 -1]^T\) vectors.

After computing eigenvalue and eigenvector for Hessian matrix of each image pixel, following conditions could be occurred:

- For bright vascular structures on a dark background if the ordering of eigenvalues are \( \lambda_1 \leq \lambda_2 \leq \lambda_3 \), \( v_1 \) indicates the direction along the vessel when \( \lambda_1 = 0 \) and \( \lambda_1 \leq \lambda_2 \approx \lambda_3 \). Based on eigenvalues of Hessian matrix, numerous vesselness filter are proposed in literature [3],[4],[5],[7]. In this work, we use the definition of vesselness function that proposed in Frangi et. al. work [5]. The formulation of vesselness measurement, proposed in [5], is as follows:

For 3D images:

\[ F(\lambda) = \begin{cases} 0 & \lambda_2 > 0 \text{ or } \lambda_3 > 0 \\ \frac{R_A^2}{(1 - e^{-2\pi^2\alpha/\lambda_2})} e^{-\frac{R_B^2}{2\beta^2} + \frac{S^2}{2\gamma^2}} & \text{o.w.} \end{cases} \]

\[ S = ||H||_F = \sum_{i \in D} \lambda_i^2 \]

\[ R_B = \frac{\lambda_1}{|\lambda_2\lambda_3|}, \quad R_A = \frac{|\lambda_2|}{|\lambda_3|} \]

And for 2D images:

\[ F(\lambda) = \begin{cases} 0 & \text{if } \lambda_2 > 0 \\ e^{-\frac{R_B^2}{2\beta^2} + \frac{S^2}{2\gamma^2}} & \text{otherwise} \end{cases} \]

\[ R_B = \frac{\lambda_1}{\lambda_2} \]

Where \( R_A \) make distinction between plate and line like structures, \( R_B \) investigates deviation from a blob like structure, and \( S \) differentiates between vessels and background. The parameters \( \alpha, \beta, \gamma \) adjust the influence of \( R_A, R_B \) and \( S \) to determine vesselness response. Hessian with Gaussian derivatives at multiple scales is computed and the highest response is considered as the output of the filter.

3. Vessel segmentation

In this section we focus on discriminate between the bright vessels and dark background. As mentioned in previous section, the vesselness filter enhances the vessels of X-ray angiographic frame and improves the contrast between vessels and the background. However, to decide whether a pixel belongs to vessel or not, applying a threshold on the filtered image using vesselness filter is inevitable. Figure 1 presents a frame from angiographic movie and its filtered version using vesselness filter. As figure 1 shows the response of vesselness filter to some of non-vessel structures of image such as human ribs is high. Consequently adjusting a threshold to detect the vessels merely could results in error in some cases.

Figure 2 presents the response of vesselness filter after applying threshold. As it is shown in figure 2, by using a low level as a threshold all of vessels are detected but some other parts such as ribs are also detected as vessels in error while for a high level threshold the ribs are removed from the response, however, some of thin vessels are also removed. It is noticeable that although some parts of vessels are removed, the direction of remaining parts is obtainable; as a result, whole of vessels can be recovered according to these directions.

Figure 1. Original image (right) and the response of the vesselness filter (left). Both of ribs and tiny vessels make collective response from vesselness filter.
In this approach, to deal with the problem of vessel segmentation, firstly a high level threshold is applied to the image to remove most of non-vessels from image. Afterward, the remaining vessels are detected and their directions are obtained. Then dilation operator is employed to expand the remaining vessels and recover the main vessels.

For better understanding, figure 3 depicts one frame of X-ray angiographic image and results of operations discussed in above. As shown in figure 3.d, dilation of vessel particles can recover the whole vessel if some amount of false positive is acceptable. Regions of image which need recovering operations are specified by red rectangles in figure 3. (c).

However, to reduce the non-vascular structures in the yielded image, as shown in figure 4, after applying a low level threshold on the vesselness filtered image, product of two images is considered as the result of the approach.

Equation 1 presents the production of results:

$$I_r(x, y) = I_{th}(x, y). I_D(x, y)$$

Where $I_r$, $I_D$ and $I_{th}$ denote the result image, dilated image and vesselness filtered image after applying low level threshold, respectively.

Finally, since for some of diagnostic applications only the main vessels are important, deletion of fine particles of image could yield a more clear result. To remove the fine particles, firstly labeling operation is accomplished in image. Afterward, the size of each label is obtained and the labels smaller than a predefined threshold are removed from image. Adjusting the size threshold for removing the particle is critical issue in segmentation of vascular structure. It depends on the minimum size of vessels to be detected. Figure 5 presents the result of algorithm after particle removal operation.
4. Experimental results

In this section to benchmark our algorithm some of X-ray angiographic frames are provided for segmentation using the proposed method. 19 angiographic frames are used to evaluate the efficiency of the algorithm. Three parameters are used as threshold in the algorithm. The block diagram of the approach is illustrated in figure 6.

As an assessment of algorithm efficiency it is compared to vessel segmentation by applying a solely threshold on the vesselness filtered image. The threshold employed for the comparison is a medium level threshold. After applying the algorithm on angiographic frames the result is compared with a version of frame that is manually labeled to determine the amount of parameters indicating the accuracy of the method. These parameters are false positive (FP), false negative (FN) and true positive (TP). False positive presents number of non-vessel pixels which are erroneously classified as vessels. While false negative means the number of pixels which are vessels but the algorithm could not detect them, finally true positives are the number of pixels which are classified correctly as vessels. Since some mistakes are made while manual labeling of vessels, true positives are counted as following way. For every pixel in the known vessels if there is a marked pixel as vessel its 3x3 neighborhood is also counted as a true positive. To evaluate the performance of the proposed method, receiver operating curve (ROC) is obtained. It presents the variation of false positive ratio (FP) versus true positive ratio (TP) for various amounts of parameters of the system. Area under the ROC curve indicates the efficiency of the method. The higher the area under ROC curve, the higher efficiency of the algorithm. In this section, two ROC curves are provided for two threshold parameters namely the high level threshold of vesselness filter and the threshold of the particle removal step. Figure 7 presents ROC curves.
Figure 8. Comparison of two method accuracies for 19 angiographic frames including the proposed method (blue line) and the method which applies one threshold on the vesselness filtered image (red line).

Figure 8 presents the comparison of efficiency of the proposed method and the method which uses a solely threshold on the vesselness filtered image. In the former method, the high level threshold and the low level threshold are 0.8 and 0.25, respectively and the threshold of particle removal step is equal to 3000 pixels, while in the latter, the threshold is equal to 0.5. As figure 8 shows, the accuracy of the proposed method exceeds the other method accuracy.

Another comparison of the method efficiencies is presented in Figure 9 when the threshold of the particle removal step is adjusted to 4400 pixels. Other thresholds are adjusted as before. As figure 9 indicates, the superiority of the proposed method is obvious.

It is worth noting that due to different characteristics of X-ray angiographic systems, the parameter adjustment should be accomplished for each angiographic system.

Figure 9. Comparison of two method accuracies for 19 angiographic frames when the particle removal threshold is adjusted to 4400 pixels. Distinct preference of the proposed method (blue line) over the other method (red line) is clear.

5. Conclusion

In this paper a method for segmentation of vessels in X-ray angiographic frames is proposed. Firstly Hessian based vesselness filter is applied to the angiographic frames to enhance the vessels. Afterward, a high level threshold is applied to the image to detect the more bright vessels in the filtered image. Then since some parts of vessels are removed as a result of threshold, for recovering the removed vessels, according to the direction of separated vessels, they are dilated to make an integrated vessel map. Meanwhile, a low level threshold is applied to the vesselness filtered image. Subsequently, the two yielded images are combined by obtaining their product; finally the particle removal is accomplished to reduce the amount of false positive. After applying the algorithm on the X-ray angiographic frames, the superiority of the method over the Hessian based vesselness filter with single threshold is demonstrated.

6. References


