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Enhancement of Coronary Blood Vessels based on Frangi's Vesselness Filter and Morphological Operations

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Abstract: *Cardiovascular diseases (CVDs) are the global cause of deaths and therefore research in modern medical image processing aims to develop a medical tools to assist the clinicians in vessel extraction, artery detection and 3D reconstruction. Vessel extraction is an important and trivial step which depends extremely on enhancement method. Extraction of coronary artery blood vessels from 3 Dimension (3D) Coronary Computed Tomography Angiography (CCTA) images is a demanding research objective to strengthen the diagnosis and therapy of coronary artery illness. This paper presents a vessel enhancement method of coronary artery blood vessels using Frangi's vesselness measure and morphological operators. In the first stage of the proposed work, Preprocessing is performed to consider only the heart region. Next Frangi's vesselness measure is calculated for the 3D CCTA images. While calculating the Frangi's vesselness measure, four different types of gradient operators are used for calculating the Hessian matrix viz., Sobel, Prewitt, central difference and intermediate difference operators. In the second stage, the vessels are enhanced by morphological operations based on top hat and bottom hat operations. These morphological operations help in further enhancing the blood vessels. The proposed methodology was applied on 12 3D CCTA dataset and evaluated using quality measures such as MSE, PSNR, SSIM and FSIM. The results obtained based on the four gradient operators are compared. The statistical test viz., one way ANOVA was carried out on the results. The proposed method using Prewitt operator is able to extract even small vessels and the results seem to be promising.*

Index Terms: *Coronary artery, Coronary computed tomography angiography (CCTA), Hessian filter, Morphological operations, Vessel enhancement.*

I. INTRODUCTION

One of the most leading global public health problems worldwide is cardio vascular diseases (CVDs). Among different types of CVDs, Coronary Artery Disease (CAD) seems to be the foremost cause of mortality. For many clinical applications, accurate detection and evaluation of the vascular structure of cardiac image are crucial to promote early detection, diagnosis, therapy and surgical planning for coronary artery associated illnesses. Acquisition of two-dimensional (2D) and three dimensional (3D) cardio vascular imaging helps in diagnosis of CADs. The most Extensively used cardiac imaging modality is Computed Tomography Angiography (CTA).

Annotation of vessel structure manually is an exhausting process, hence various automatic or semiautomatic vessel detection methods are developed[1]. However, computer-aided systems still have to address issues like artifacts that appear during the acquisition of images such as noise, bad contrast and poor resolution. It's been proven that vessel enhancement or segmentation methods solves the mentioned problems and helps in providing accurate vessel structure [2].

Enormous research has been rendered towards vessel enhancement and detection in Coronary Computed Tomography Angiography (CCTA) images. Some authors proposed 3D vessel detection techniques for detecting vessels from medical images based on "region growing" [3-7] and "tracking based methods" [8-12]. These approaches use information such as contrast, origin of arteries and connectivity of the vessels. Shant et al presented a "minimum cost path" technique for extracting CTA information [13] from the centerlines of cardiac images. Similarly various vessel detection techniques for medical images works using "minimum cost path" method [13-15].

Yan et al [16] described a vesselness measure with high overlap and reliability measurements to discard unwanted step-edge responses of cardiac chamber borders . Kristína et al [17] presented a skeleton based vesselness measure to differentiate lines and edges to permit the tolerance of vessels with irregular appearance. As a consequence, under typical imaging circumstances their filter demonstrates a powerful response to the vascular attributes. Mohammad et al[18] proposed a non-parametric geodesic active regions (GAR) technique and offered promising vasculature and aneurysm segmentation results. Though numerous research has been done on vessel enhancement and detection, it still remains to be a demanding problem, due to the complex vessel structure, reconstruction artifacts and vessel overlaps [19]. Frangi's vesselness measure is most frequently used filter for enhancement of cardiac vessels. But it has some limitations such as 1) vesselness measure is poor for voxels which are nearer to the boundary of the blood vessel and 2) usage of Gaussian filters during Frangi's vesselness filtering leads to blurring of boundaries of blood vessels. In order to eliminate these limitations, morphological operations such as "top hat" and "bottom hat" filtering operations are implemented on the results obtained from Frangi's vesselness measure.

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These morphological operations help in further enhancing the blood vessels. The morphological opening in top hat filtering helps in further enhancing the voxels with strong vesselness measures and the closing in bottom hat filtering helps in further eliminating the voxels with less vesselness measures.

Hence both "top hat" filtering and "bottom hat" filtering enable to further enhance the vesselness measures obtained using Frangi's filter. In the present work, while computing the Hessian matrix four different gradient operators such as (1) Sobel operator, (2) Prewitt operator, (3) Central difference operator and (4) Intermediate difference operator are used.

The proposed method for coronary blood vessel enhancement based on Hessian based vesselness filter and top hat, bottom hat morphological operations are described in section II. In section III, the experimental results and discussion are provided and the performance of the proposed method is evaluated. Section IV provides the conclusion.

II. PROPOSED METHOD

Fig 1 presents the architecture of the proposed methodology. The proposed methodology enhances the coronary artery blood vessels from 3D CCTA images in three steps viz., preprocessing, Hessian based vesselness filtering and morphological operations. The following subsections describe the steps of proposed methodology.

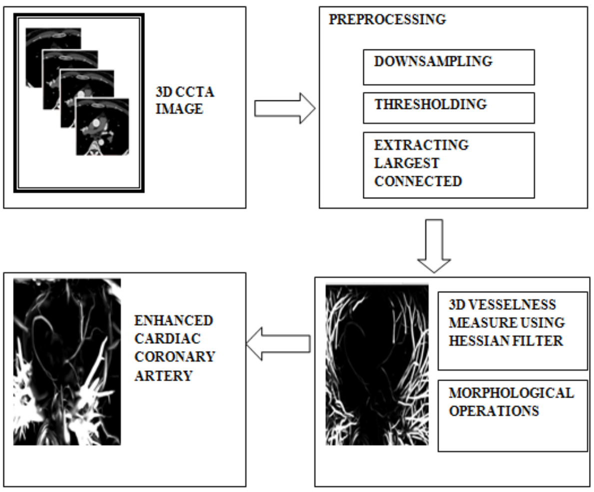
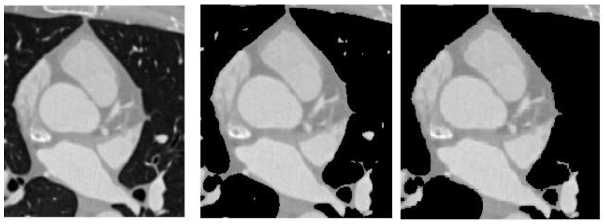


Figure.1 Proposed processing pipeline for enhancement of coronary artery vessels

III. PREPROCESSING

In order to eliminate as many blood vessels in the lung region, preprocessing steps need to be performed initially. Every three dimensional (3D) CCTA volume has a set of 2D images with a dimension of 512x512 pixels. These 2D images are downsampled by a factor of 2 using linear interpolation and the resulting dimension is 256x256 pixels. This downsampling helps in reducing the computation time. Then the thresholding is performed to set the voxels having intensities greater than 676 HU as 0 so that calcifications, stents, bones and other regions can be removed [20]. Later, in order to consider only the heart region, the largest connected component is retained. The preprocessing results are shown in fig 2.



(a) (b) (c)

Figure.2 Stages of Preprocessing phase:(a) Original image
(b) After thresholding (c) Largest connected component

IV. HESSIAN BASED FILTERING

One of the major challenges in diagnosing CAD is to enhance the cardiac vessels in cardiac images and use it for further processing such as for quantifying calcifications or stenoses. Hessian filter is most widely used for enhancing coronary vessels from heart muscle. The Hessian matrix is composed of second order gradients of image which is defined in the following equation (1):

$$H(I) = \begin{bmatrix} \frac{\delta^2 I}{\delta x^2} & \frac{\delta^2 I}{\delta x \delta y} & \frac{\delta^2 I}{\delta x \delta z} \\ \frac{\delta^2 I}{\delta y \delta x} & \frac{\delta^2 I}{\delta y^2} & \frac{\delta^2 I}{\delta y \delta z} \\ \frac{\delta^2 I}{\delta z \delta x} & \frac{\delta^2 I}{\delta z \delta y} & \frac{\delta^2 I}{\delta z^2} \end{bmatrix} \quad (1)$$

where I(x,y,z) represents an image and the elements of H are second order gradients of the 3D CCTA image. The Hessian matrix can also be represented as shown in equation (2):

$$H = J(\nabla I(x,y,z)) \quad (2)$$

where J represents the Jacobian matrix [21]. In the present work in order to compute $(\nabla I(x,y,z))$, four different types of first order derivative operators such as: 'Sobel', 'Prewitt', 'Central difference' and 'intermediate difference' have been used. The Sobel operator or filter computes the difference of pixel intensities in an edge region.

At each point, it calculates the gradient of the image inten sity and then provides the direction to improve the intensity of the edge. Thus it becomes enhanced comparatively to the original image. The 3D Sobel filter used in this work is given in fig 3.

-2	0	2
-3	0	3
-2	0	2

(a)

-3	0	3
-6	0	6
-3	0	3

(b)

-2	0	2
-3	0	3
-2	0	2

(c)

Figure.3 3D Sobel filter along (a) x-direction,(b)y-direction, (c)z-direction.

Prewitt operator works by convolving the image in horizont al(x) and vertical(y) direction with a small, separable and int eger-value filter. It estimates the magnitude and orientation of an edge used in images to detect vertical and horizontal edges. The 3D Prewitt filter used in the present work is specified in fig 4.

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-1	0	1
-1	0	1
-1	0	1

-1	0	1
-1	0	1
-1	0	1

-1	0	1
-1	0	1
-1	0	1

(a) (b) (c)

Figure.4 3D Prewitt filter along (a) x-direction (b)y-direction (c)z-direction.

The gradient using intermediate difference operator is computed by taking the difference of a current voxel and one into intermediate neighbor. The intermediate difference kernel operator for each direction is given as shown in equation (3):

$$D_{x,y,z} = [-1,1] \quad (3)$$

The Central difference operator is similar to immediate difference operator. The gradient using Central difference operator is computed by considering the difference of the current voxel and two of its neighbours. The Central difference kernel operator for each dimension is given by equation (4):

$$D_{x,y,z} = [-1,0,1] \quad (4)$$

Once the Hessian matrix is computed, the Eigenvalue analysis is performed on the Hessian matrix in order to extract one or more principal directions of the local structure of the image [22]. The Eigenvalues of H ($\lambda_1, \lambda_2, \lambda_3$) with its equivalent Eigenvectors (e_1, e_2, e_3), define the orthogonal coordinate system associated with the direction of minimal (e_1) and maximal (e_3) curvature. For a vessel, e_1 indicates the orientation of the vessel. Thus λ_1 represents the parallel curvature and λ_2 and λ_3 the orthogonal curvatures. To detect the vessels, the eigen values should be related as follows: $|\lambda_1| < |\lambda_2|, |\lambda_3|$ and $|\lambda_2| \sim |\lambda_3|$. Also for bright blood images $|\lambda_1| \sim 0$ and $\lambda_2, \lambda_3 > 0$. Therefore the overall magnitude of the Eigen values of blood vessels should be larger than the Eigen values calculated in background regions. The Frangi filter defines the following equations in term of the Eigen values of the Hessian matrix [22]:

$$R_A = \left[\frac{|\lambda_2|}{|\lambda_3|}\right] \quad (5)$$

$$R_B = \left[\frac{|\lambda_1|}{|\sqrt{T\lambda_2\lambda_3}|}\right] \quad (6)$$

If R_A is 0, it refers a plane. If R_B is 1,it implies a line. The measure S is used to differentiate between cardiac vessel and heart muscle (ie) S indicates the relative brightness or darkness of the vessel structure and is calculated by (7):

$$S = \sqrt{\lambda^2{}_1 + \lambda^2{}_2 + \lambda^2{}_3} \quad (7)$$

A smaller value of S implies that the voxel belongs to background and a larger value of S implies that the voxel is close to the centerline of the cardiac vessel. These quantities are combined using exponentiation, assuming a bright blood image, to give a ''vesselness'' measure defined as follows:

$$V = \begin{cases} 0, if\ \lambda_2 > 0\ or\ \lambda_3 > 0, \\ \left(1 - exp\left(-\frac{R^2 A}{2\alpha^2}\right)\right) .\exp\left(\frac{R^2 B}{2\beta^2}\right).\left(exp\left(\frac{S^2}{2\lambda^2}\right)\right) \\ otherwise, \end{cases} \quad (8)$$

where α, β, γ represent the weights (ie) the sensitivity of the filter to the resultant measures.

The exponential function is used to map the vesselness measure to a value between 0 and 1.

V. ENHANCEMENT OF VESSELS USING TOP-HAT AND BOTTOM HAT BASED MORPHOLOGICAL OPERATIONS

In the present work, top-hat and bottom-hat filters are used together to improve the vesselness measures obtained from the previous step.

The top-hat transformation is a morphological approach that utilizes the structuring element SE [23] to calculus ate the morphological opening of the image and then subtra ct the result from the original image.

$$V_{Enhance} = V - (V \circ b) \quad (9)$$

where b represents the structuring element, V is the vesselness measure obtained from the previous step, o represents opening operator. In the present work the structuring element b used is represented as shown in equation (10):

$$b = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad (10)$$

Bottom-hat filtering is a morphological approach that utilizes the structuring element SE [23] to compute the morphological closing of the image and then subtracts the result from the original image. The closing operation in bottom-hat filtering helps in helps in reducing the vesselness measure of voxels which are very less. This helps in converting the voxels with lesser vesselness measure as background. Bottom-hat filtering is defined using equation (11):

$$V_{Enhance} = V - (V \bullet b) \quad (11)$$

where b represents the structuring element, V is the vesselness measure obtained from the previous step, • represents closing operator. Hence the "top hat" and "bottom hat" filtering are used together with hessian matrix to enhance the obtained Frangi's vesselness measure.

VI. EXPERIMENTAL RESULTS AND DISCUSSION

The cardiac CTA images used in this research were obtained from KG hospital, Coimbatore. Totally 3D cardiac images of 12 patients are used in this work. The CCTA images are in DICOM format (Digital Imaging and Communications in Medicine) which were acquired with 1.2mSv and 0.2mSv. Every CCTA volume has at least 200 slices with the dimension of each slice being 512x512 voxels. Fig 5 shows the maximum intensity projection (MIP) of pre processed 3D CCTA and enhanced vessels using the proposed method. The results of enhanced vessels using Sobel, Prewitt, central difference and intermediate difference operator based Frangi's vesselness measure and morphological operations are provided. It can be seen from the results that Prewitt operator based Frangi's vesselness measure with morphological operations is able to enhance the coronary artery blood vessels in a better manner. The quantitative results obtained from Sobel, Prewitt, central difference and intermediate difference gradient operators based Frangi's vesselness measure and morphological operations are also compared.

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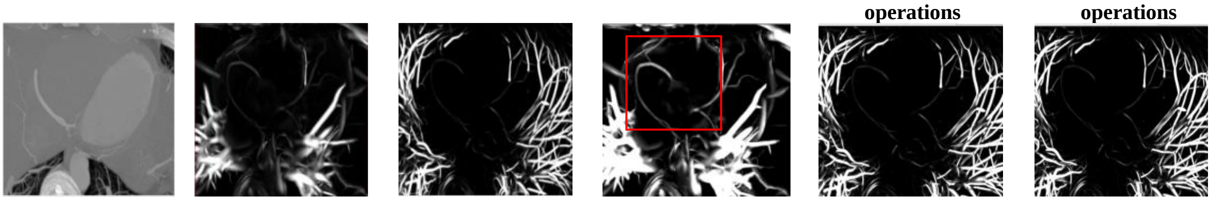
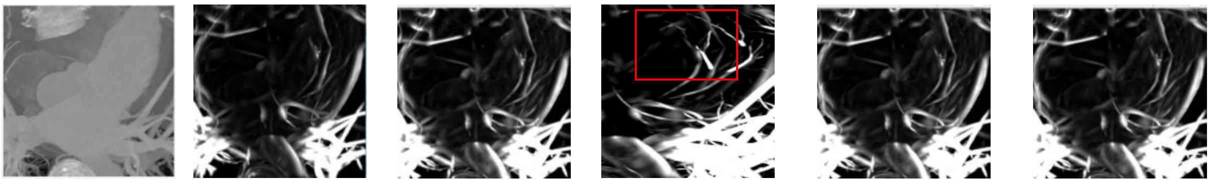
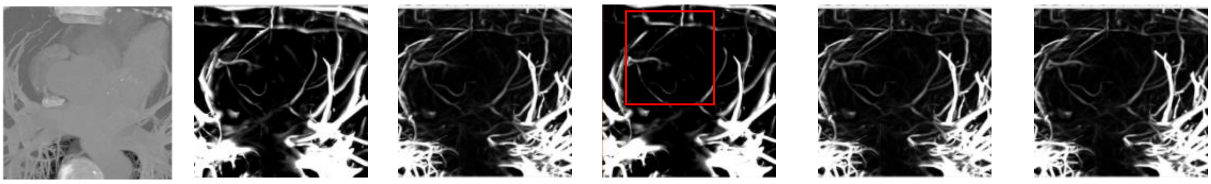
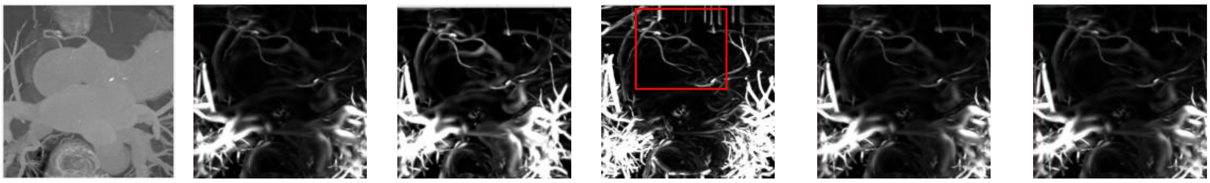
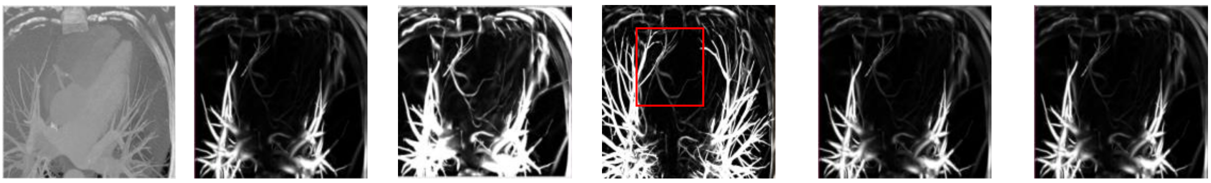
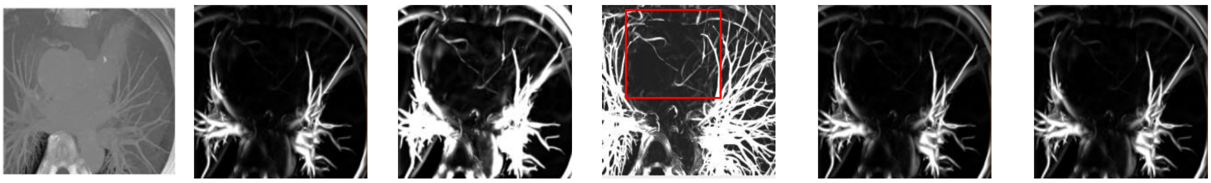
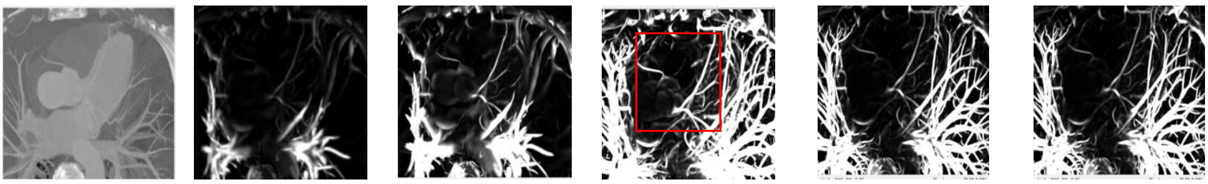
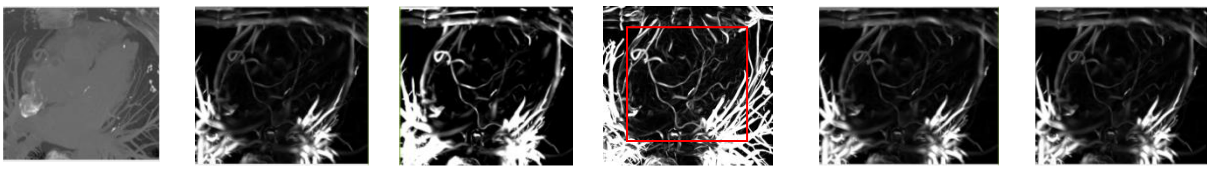
Dataset . No	Pre-processed 3D CCTA volume	Frangi's Vesselness measure	Sobel operator based Frangi's vesselness measure and morphological operations	Prewitt operator based Frangi's vesselness measure and morphological operations	Central difference operator based Frangi's vesselness measure and morphological operations	Intermediate difference operator based Frangi's vesselness measure and morphological operations
1						
2						
3						
4						
5						
6						
7						
8						

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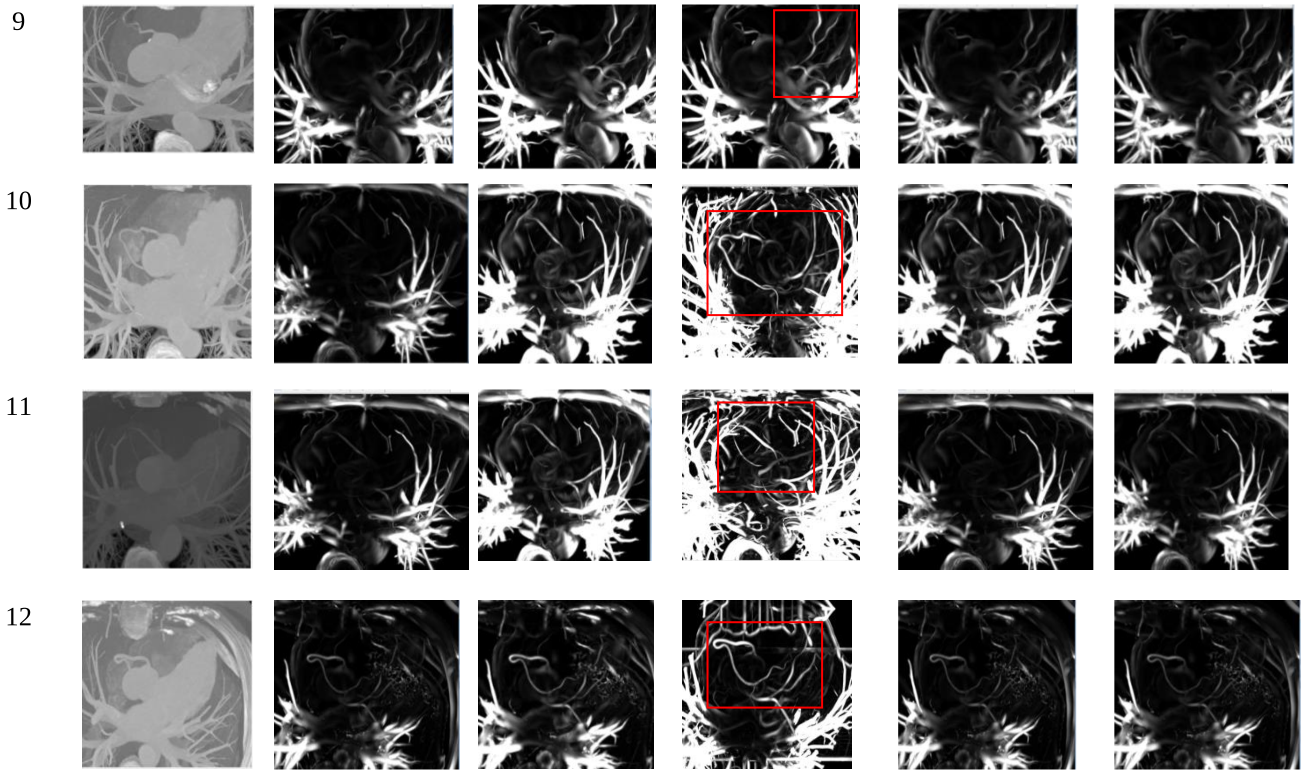

Figure.5 Qualitative evaluation of proposed method

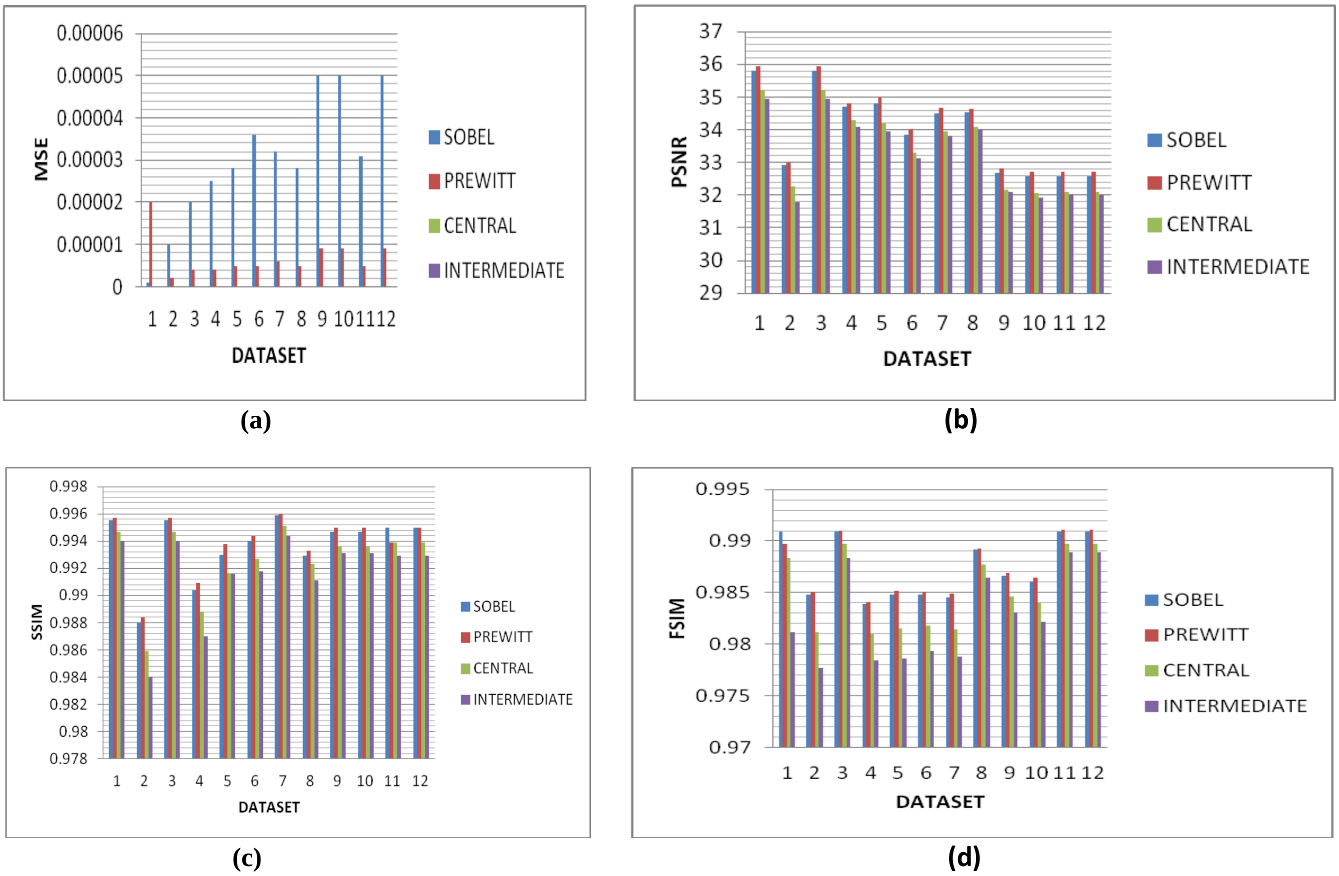

Figure.6 Comparison of results obtained using proposed vessel enhancement method based on Sobel, Prewitt, central difference and intermediate difference operators (a) MSE,(b) PSNR,(c)SSIM, (d)FSIM.

Table 1. Performance results of enhanced vessels using Sobel, Prewitt, central difference and intermediate difference operator using Frangi's vesselness measure and morphological operations based on (a) PSNR,(b)SSIM, (c)FSIM.

(a)

SOBEL	PREWITT	CENTRAL	INTERMEDIATE
35.814	35.9474	35.2221	34.9423
32.9099	33.0031	32.2727	31.793
35.814	35.9474	35.2221	34.9423
34.7206	34.7911	34.3071	34.0762
34.7911	34.9738	34.1949	33.9428
33.854	34.0193	33.2874	33.1201
34.5126	34.6657	33.9399	33.7998
34.5393	34.6345	34.0944	34.0159
32.6772	32.8265	32.1496	32.0849
32.5687	32.7065	32.0641	31.9265
32.5772	32.6975	32.0823	32.0115
32.5772	32.6975	32.0823	32.0115

(b)

SOBEL	PREWITT	CENTRAL	INTERMEDIATE
0.9955	0.9957	0.9947	0.994
0.988	0.9884	0.9859	0.984
0.9955	0.9957	0.9947	0.994
0.9904	0.9909	0.9888	0.987
0.993	0.9938	0.9916	0.9916
0.994	0.9944	0.9927	0.9918
0.9959	0.996	0.9951	0.9944
0.9929	0.9933	0.9923	0.9911
0.9947	0.995	0.9936	0.9931
0.9947	0.995	0.9936	0.9931
0.995	0.9939	0.9939	0.9929
0.995	0.995	0.9939	0.9929

(c)

SOBEL	PREWITT	CENTRAL	INTERMEDIATE
0.9909	0.9897	0.9884	0.9812
0.9848	0.9851	0.9812	0.9777
0.9909	0.991	0.9897	0.9884
0.9839	0.9841	0.981	0.9784
0.9848	0.9852	0.9815	0.9786
0.9848	0.9851	0.9818	0.9793
0.9845	0.9849	0.9814	0.9788
0.9892	0.9893	0.9877	0.9864
0.9866	0.9869	0.9846	0.9831
0.9861	0.9864	0.984	0.9822
0.9909	0.9911	0.9897	0.9889
0.9909	0.9911	0.9897	0.9889

Table 2. P-values for the one-way ANOVA test for the FSIM of Sobel, Prewitt, Central and Intermediate vesselness measure

Source of Variation	SS	df	MS	F	P-value	F critical
Between Results obtained using Frangi's vesselness measure and Proposed vesselness measure	0.00014	3	0.000049	3.872	0.01603	2.84

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Mean Square error (MSE), Peak signal to noise ratio (PSNR), Structural Similarity Index Matrix(SSIM) and Feature Similarity Index matrix (FSIM) are used as metrics to evaluate the performance of the proposed vessel enhancement method. Fig 6 provides the comparison based on MSE, PSNR, FSIM and SSIM for the original image and vessel detected image using the proposed vessel enhancement method.

The higher the PSNR value, the better the quality of the reconstructed image. In terms of PSNR the proposed vessel enhancement method based on Prewitt operator gives higher value and hence is better compared to other gradient operators. Lower value of MSE assures less error in image information. Even in terms of MSE the proposed vessel enhancement method based on Prewitt operator is better as it has the least average MSE. Similarly SSIM is used for measuring the similarity between two images. SSIM value based on Prewitt gradient operator is higher compared to other gradient operators. FSIM value measures the feature similarity between the images. FSIM value based on prewitt gradient operator is higher compared to other gradient operators. Table 1 provides the performance results of enhanced vessels using Sobel, Prewitt, central difference and intermediate difference operator using Frangi's vesselness measure and morphological operations based on the above measures. The obtained results in terms of PSNR, MSE, SSIM and FSIM show that the proposed vessel enhancement method based on Prewitt operator extracts the vessel segments more effectively.

A one-way (Analysis of Variance) ANOVA is used to analyze the difference between FSIM values obtained from vessel enhancement using Frangi's vesselness measure and the proposed method with four different gradient operators. Table 2 summarizes the results of one-way ANOVA test with significant level (alpha) of 0.05 performed on FSIM values obtained using Frangi's vesselness measure and proposed method. The p-value obtained is 0.01603 which is less than 0.05 (alpha). Hence, the results obtained using the proposed method are significant. Similarly the F critical value, 2.84, is lesser than the F-value, 3.872. This fact again proves that the proposed vessel enhancement method based on Frangi's vesselness measure and morphological operations is better compared to vessel enhancement method using Frangi's vesselness measure.

VII. CONCLUSION

In this paper, an improved vessel enhancement method is proposed which is based on Frangi's vesselness measure, morphological operations. While calculating the Hessian matrix four different gradient operators viz., Sobel, Prewitt, central difference and intermediate difference are used, which helps to detect all the vessels of the cardiac image. It can effectively suppress the noise and can extract small and distant vessels. Later, morphological operations based on top-hat and bottom-hat filtering are performed on the obtained vesselness measures to further enhance them. The proposed vessel enhancement method has been evaluated using 12 3D CCTA images and the results are encouraging. Thus the method can effectively enhance vascular structure and suppress the pseudo vascular structures. The statistical analysis also proves that the proposed method can extract the enhanced vessel segments more effectively from the background.

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