A Novel Trilateral Filter for Digital Subtraction Angiography

Purvi Tripathi[1], Richard Obler[2], Andreas Maier[1], Hendrik Janssen[3]

[1]Pattern Recognition Lab, Friedrich-Alexander-University Erlangen-Nürnberg
[2]Department of Interventional Radiology, Advanced Therapies, Siemens Healthineers GmbH, Forchheim
[3]Institute for Neuroradiology, Center for Radiology and Neuroradiology, Hospital of Ingolstadt, Ingolstadt
purvi.tripathi@fau.de

Abstract. In this paper, we formulate a novel Trilateral Filter (TF) for denoising digital subtracted angiography (DSA) without losing any vessel information. The harmful effect of X-rays limits the dose resulting in degraded signal-to-noise ratio (SNR). A bilateral filter (BF) is often applied for edge-preserving denoising. However, for a low SNR image, the filter needs to be iterated with smaller spatial window to avoid over-smoothing of low-contrast vessels. The proposed TF combines the BF of wider spatial window with the Frangi vessel enhancement filter to denoise the DSA and to improve the vessel visibility without the need for iteration. The experimental results shows that our method provides better vessel preservation and greater noise reduction than the BF.

1 Introduction

X-ray angiography is one of the most common and widely practiced forms of interventional radiology. It is often used to produce fluoroscopic images while guiding within the blood vessels [1]. Despite being an effective non-invasive medical imaging technique, X-rays can cause significant damage to the human body. The ionizing radiation of X-rays is a high energy electromagnetic radiation that partially penetrates the tissues to produce images of inner structures [2]. Exposure to ionizing radiation can damage human tissues deterministically (radiation burn) and impair the DNA stochastically [3]. The latter may cause cancer or heritable effects, thus labeling X-rays as carcinogenic [4]. To ensure minimal exposure, all medical examinations are performed following the ALARA-principle (As Low As Reasonably Achievable) [5]. However, reducing the X-ray dose results in an image with a degraded signal-to-noise ratio (SNR).

It is well established that a clear and accurate vascular representation is an essential aspect of any angiographic imaging. A noisy medical image is not only visually frustrating but also perplexes the diagnosis and intervention. The image processing pipeline of an interventional radiology system applies various filters to enhance the visibility of clinically relevant aspects, such as vessel contrast and vessel edge definition. Since there is an on-going demand to further reduce the X-ray dose, which will consequently result in an image with even lower SNR, there is a strong need to further improve the performance of filters for angiographic images.

A bilateral filter is commonly used to denoise medical images while preserving edges. However, to avoid over-smoothing of low-contrast vessels in Digital Subtracted Angiography (DSA), the filtering is performed using a smaller spatial window leading to more number of iterations. In this paper, we propose novel trilateral filtering for DSA that can effectively reduce noise while preserving all the vessels without any iterations. The technique uses the Frangi vessel enhancement filter to identify the vessels and define the structural similarity. The structural similarity is integrated along with the geometric and photometric similarity of the BF to achieve vessel-preserving smoothing.

2 Materials and methods

2.1 Bilateral filter

A bilateral filter is an edge-preserving non-linear filter proposed by Tomasi et al [6] The main principle of a BF is that two pixels are considered neighbors not only when it is spatially close but also if it has similar photo-metric value. It is mathematically defined as

$$BF[I]_p = \frac{1}{W_p} \sum_{q \in S} G_{\sigma_s}(\| p - q \|) \cdot G_{\sigma_r}(\| I_p - I_q \|) I_q \tag{1}$$

where I_p and I_q are pixel intensity at pixel location p and q, respectively. S is the spatial window around p, and W_p is a normalization factor given by

$$W_p = \sum_{q \in S} G_{\sigma_s}(\| p - q \|) \cdot G_{\sigma_r}(\| I_p - I_q \|) \tag{2}$$

The amount of filtering in image I is controlled by parameters σ_s and σ_r. Equation (1) is a normalized weighted average where G_{σ_s} is a spatial Gaussian that regulates the effect of pixel-based on proximity, i.e., a closer pixel will result in more change to the center pixel p, and G_{σ_r} is a range Gaussian that decreases the effect of the pixel with higher intensity difference. It has been indicated in [7] that a BF with a wider kernel can lead to over-smoothing of the low-contrast vessel. To avoid that, the filter is often iterated increasing the computation time.

2.2 Frangi vessel enhancement filter

The vessel information is the most crucial aspect of interventional radiology. It is imperative to have a precise and clear vascular visualization and segmentation for clinical procedures. Frangi vesselness filter [8] is one of the most commonly used vessel enhancement techniques and is based on eigenvalue analysis of the Hessian matrix. The Hessian matrix is calculated by smoothing the image with a multiscale second order of the Gaussian (G_σ)

$$H_\sigma = G_\sigma * I = \begin{bmatrix} H_{xx} & H_{xy} \\ H_{xy} & H_{yy} \end{bmatrix} \tag{3}$$

The matrix is decomposed to calculate the two principle eigenvalues λ_1 and λ_2 [9]

$$\lambda_{1,2} = \frac{(H_{xx} + H_{yy}) \pm \sqrt{(H_{xx} - H_{yy})^2 + 4H_{xy}^2}}{2} \tag{4}$$

Analysis of the Hessian is performed to extract the principal local direction of curvature. The direction of curvature will be the smallest along the vessel. The pixels that are within the vessel will have a λ_1 close to zero and a large value for λ_2 [8]. A tubular structure is identified if it satisfies the following conditions:

$$\lambda_1 \approx 0 \tag{5}$$

$$\|\lambda_2\| \gg \|\lambda_1\| \tag{6}$$

Based on the second order ellipsoid, a ratio R_B is defined that describes blob-like structures or blobness. It is used to distinguish between line-like structure and plate-like structure and is given as

$$R_B = \frac{\|\lambda_1\|}{\|\lambda_2\|} \tag{7}$$

Further, a norm of Hessian matrix is used to measure the structureness, S. The structureness will be low for the region with low contrast and no structure. But in the region with high contrast, one of the eigenvalues will be large, and hence the value for S will be high [8]

$$S = \sqrt{\lambda_1^2 + \lambda_2^2} \tag{8}$$

Using R_B and S, the vesselness V_o is defined as

$$V_o(\sigma) = \begin{cases} 0, & \text{if } \lambda_2 > 0 \\ \exp(-\frac{R_B^2}{2\beta^2})(1 - \exp(-\frac{S^2}{2c^2})), & \text{otherwise} \end{cases} \tag{9}$$

where β, c are image-dependent parameters for blobness and structureness, respectively. For DSA images, the tubes are darker, and the lambda condition is reversed to $\lambda_2 < 0$. The σ used to calculate the Hessian matrix is used over a certain range, where the minimum σ depicts the detection of the smallest structure and maximum σ is for the biggest structure. For the cerebral DSA, we chose σ as 3, 5, and 7.

2.3 Trilateral filter

In this paper, we propose a novel trilateral filter as an extension of the BF to smooth a low-SNR DSA with wide kernel to maintain the denoising effect of a BF while preserving the low-contrast vessels. Along with the geometric and photometric similarity of a BF, the filter considers structural similarity (vesselness) as the third parameter, extracted using the Frangi vessel enhancement filter. The filter is mathematically defined as

$$TF[I]_p = \frac{1}{W_p} \sum_{q \in S} G_{\sigma_s}(\| p - q \|) \cdot G_{\sigma_r}(\| I_p - I_q \|) \cdot G_{\sigma_v}(\| V_p - V_q \|) I_q \quad (10)$$

where W_p is a normalization factor

$$W_p = \sum_{q \in S} G_{\sigma_s}(\| p - q \|) \cdot G_{\sigma_r}(\| I_p - I_q \|) \cdot G_{\sigma_v}(\| V_p - V_q \|) \quad (11)$$

The V_p and V_q are the normalized vesselness value drawn from the Frangi vesselness filter at a similar pixel location as that of the original image, and σ_v is the standard deviation for the vesselness. The principle of vessel preservation in the trilateral filter is similar to that of edge preservation. If the neighboring pixel has the same vesselness as that of the center pixel, its weight is higher than the pixel that is less similar. One of the features of the proposed filter is that for a region with no vessel, the vesselness is 0 resulting in vesselness Gaussian of 1. Therefore, the weight of the filter at those regions will be the same as the BF. Since the angiographic images are rarely flat, the vesselness difference between the vessel's pixels is mostly a non zero value, resulting in an additional smoothing within the vessel. The phenomenon together ensures controlled denoising and improves the visibility of low contrast vessels.

For our study, we selected wide kernel size of 21, with $\sigma_s = 6.0$, $\sigma_r = 15.0$, and $\sigma_v = 0.0005$. The filter first performs a Frangi vessel enhancement and stores the normalized vessel map as a new image. The original image and vessel map, along with the required parameter is passed for the trilateral filtering. For creating comparable results, we processed the image with both BF and TF with constant common parameters. Unlike the trilateral filtering approaches described by [10], with a favorable setting, this approach does not require iterations.

The DSA used in this study were acquired using ARTIS Biplane© (manufactured by Siemens Healthcare GmbH) at Center for Radiology and Neuroradiology, Hospital of Ingolstadt. To qualitatively evaluate the performance of the filter, we processed 15 DSA scenes of various dose levels using both the filters. The two filter techniques were ranked by four medical professionals based on the visual benefits. Quantitatively, we selected 10 high dose images and added Gaussian noise of standard deviation 7 and random Poisson noise to it. The images were then filtered and compared to the original image using two metrics: structural similarity index measure (SSIM), which is relevant for structural preservation, and peak signal to noise ratio (PSNR), relevant for noise reduction. The average of the 10 readings is accounted for the final comparison.

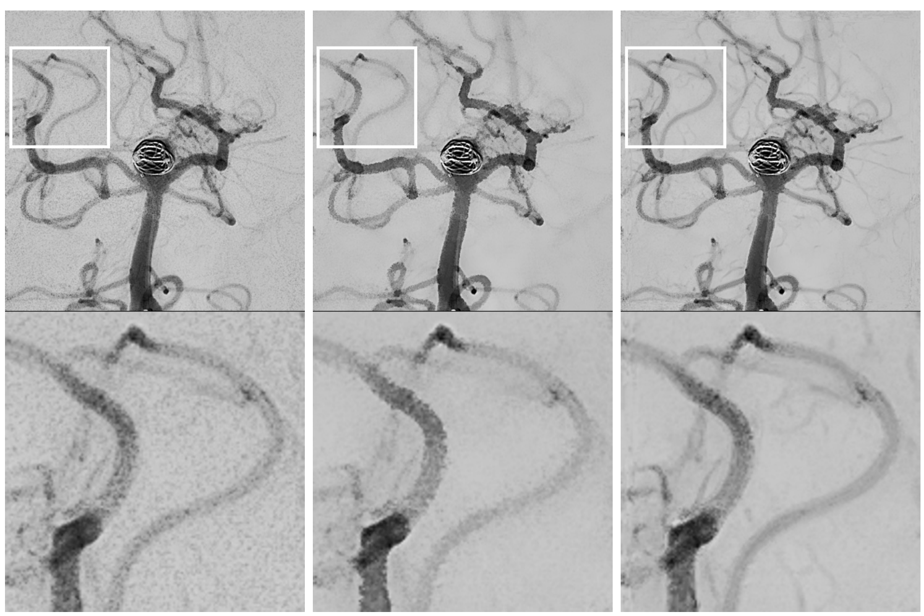
3 Results

As per the observer study conducted by the medical experts, the proposed TF shows a clear preference over the BF. For the 60 samples in study, the proposed TF was the preferred technique for 55 samples. A comparison of both filter approaches is shown in Fig 1. Fig 1(b) shows the over-smoothing effect of the BF. Also, the poor noise reduction around the bigger vessel reduces the visibility of the vessel. On the contrary, the TF in Fig 1(c) not only preserves the fine structures, but the additional smoothing within the vessels compensates for the contrast loss occurring due to bilateral filtering.

The quantitative comparison of the proposed TF with the BF is summarized in Table 1. The results show an increase in both SSIM and PSNR between BF and TF. With the selected parameter, the proposed filter performs the best for the reduction of Gaussian noise achieving an increase of 37% and 10% for SSIM and PSNR, respectively.

4 Discussion

In this paper, we proposed a combination of the BF and Frangi vessel enhancement filter to formulate the novel Trilateral filter for DSA, to perform vessel-preserving denoising. The proposed filter considers geometric, photometric, and



(a) Original (b) BF (c) TF

Fig. 1. Low-dose DSA. (a) Original image; denoised image with (b) Bilateral Filter and (c) Trilateral Filter. Source image courtesy: Center for Radiology and Neuroradiology, Hospital of Ingolstadt.

Table 1. SSIM and PSNR measure for low-dose DSA.

Noise	SSIM		PSNR	
	BF	TF	BF	TF
Gaussian	0.40	0.55	20.48	22.55
Poisson	0.27	0.31	17.55	18.32
Gaussian & Poisson	0.26	0.31	17.38	18.25

structural similarity in a wider neighborhood as a basis of filtering. The experiment with selected parameters shows an improvement in terms of noise reduction and vessel preservation both quantitatively and qualitatively. The results of the proposed TF are very promising, especially in accordance with the observer study.

Though the filter in its current state has no visible disadvantages, vessel like artifacts with very low-contrast are a potential drawback of the TF. Further research is necessary to explore this problem and improve the filter's efficiency by automatically adapting the parameters. We shall also investigate other vessel enhancement methods to be combined with the BF. The filter shall also be extended to process images from other modalities like MRI.

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