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Original Article

Speckle Noise Reduction for the Enhancement of Retinal Layers in Optical Coherence Tomography Images

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Abstract

Introduction
One of the most important pre-processing steps in optical coherence tomography (OCT) is reducing speckle noise, resulting from multiple scattering of tissues, which degrades the quality of OCT images.
Materials and Methods
The present study focused on speckle noise reduction and edge detection techniques. Statistical filters with different masks and noise variances were applied on OCT and test images. Objective evaluation of both types of images was performed, using various image metrics such as peak signal-to-noise ratio (PSNR), root mean square error, correlation coefficient and elapsed time. For the purpose of recovery, Kuan filter was used as an input for edge enhancement. Also, a spatial filter was applied to improve image quality.
Results
The obtained results were presented as statistical tables and images. Based on statistical measures and visual quality of OCT images, Enhanced Lee filter (3×3) with a PSNR value of 43.6735 in low noise variance and Kuan filter (3×3) with a PSNR value of 37.2850 in high noise variance showed superior performance over other filters.
Conclusion
Based on the obtained results, by using speckle reduction filters such as Enhanced Lee and Kuan filters on OCT images, the number of compounded images, required to achieve a given image quality, could be reduced. Moreover, use of Kuan filters for promoting the edges allowed smoothing of speckle regions, while preserving image tissue texture.

Keywords: Pre-Processing, Speckle, Recovery, Enhancement, Evaluation.

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1. Introduction

In medical image processing, image denoising has become an essential diagnostic practice [1]. Optical coherence tomography (OCT) was introduced in 1993 as a non-contact, non-invasive imaging technique, used to obtain high-resolution, cross-sectional images of the retina. OCT was developed through a collaborative work between the New England Eye Center at Tufts University School of Medicine, Department of Electrical Engineering and Computer Sciences and Lincoln Laboratory at Massachusetts Institute of Technology [2].

OCT is based on optical techniques and coherence properties of light-infrared interferometers [3]. Medical imaging methods such as OCT, as well as other imaging modalities, involving a coherent light source, are widely popular, given their low cost and less harm to the human body. However, these modalities have major disadvantages such as speckle noise [3, 4].

Various physical techniques have been applied to remove noise from OCT images [5]. However, such methods require significant changes to the design of OCT systems and longer data acquisition time; also, in most cases, the effects of speckle denoising are insignificant. Therefore, development of algorithmic approaches for speckle noise reduction remains an integral part of OCT pre-processing [6].

Some earlier techniques include the zero adjustment procedure (ZAP) and CLEAN algorithms (originally proposed by Jan Hogborn), based on iterative deconvolution, developed originally for application in radio astronomy. Standard adaptive spatial filters such as Lee, Kuan and Frost filters have been widely used to reduce speckle in synthetic-aperture radar, ultrasound and OCT images. These filters use the second-order statistics within a minimum mean square error (MSE) and are based on a multiplicative speckle model [7, 8].

The Median filter calculates the median value in the local neighborhood of each pixel. This filter also smoothes the image and removes the edges or sharp features in the image; therefore, output of the edges is eliminated. In addition, Wiener2 filter tailors itself to the local image variance, while having a lower PSNR, compared to other adaptive filters [9].

In this study, in order to reduce speckle noise, statistical filters with different masks were applied on OCT and test images with different speckle noise variances. Objective evaluation of both types of images was performed, using various image metrics.

2. Materials and Methods

2.1. Data base records

According to Figure 1, speckle noise reduction and retina resolution restoration were performed by using a number of methods such as edge detection in OCT images. In order to reduce the noise, statistical filters including Mean, Median, Wiener2, EnLee and Kuan filters with different masks in speckle noise variances of 0.02, 0.2 and 0.59 were applied on B-scan images (cross-sectional OCT images) and the test image [11, 12]. Test image was used to facilitate the analysis of visual features from statistical filters, applied on OCT images. Comparison of numerical values of filter assessment in statistical filters can be a good approach for choosing the best statistical filters.

Various image metrics including peak signal-to-noise ratio (PSNR), root mean square error (RMSE), correlation coefficient (Corr.) and elapsed time were selected the best type of filters (EnLee and Kuan filters). The Kuan filter was selected as an input filter to enhance the edges of images in speckle noise variance of 0.02. This filter was applied to Laplacian, Prewitt, Sobel and Sobel & Prewitt masks to detect edges. Finally, For the purpose of recovery, Kuan filter was used as an input for edge enhancement.

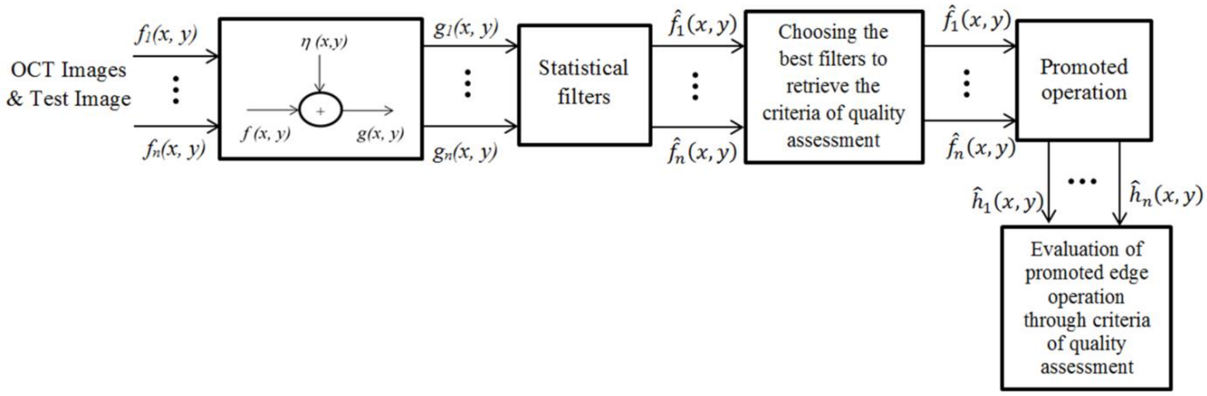

Figure 1. Process of speckle noise reduction in the present study

2.2. Speckle noise model

Access to an accurate and realistic model of speckle noise is a prerequisite for improving the algorithm of noise removal. Table 1 shows the mathematical model of speckle noise, where *g*, *f*, *u* and *V* represent the logarithms of noisy image, original image, multiplicative speckle noise and collective speckle noise, respectively. Also, m and n represent the rows and columns of the image.

Table 1. Speckle noise model and statistical filter recovery

Features	Equations	Relationship Number
Speckle noise	$g_I(n,m) = f_I(n,m)u_I(n,m)$ $g(n,m) = f(n,m)u(n,m) + \varsigma(n,m)$	(1)
Mean filter	$\hat{f}(x,y) = \frac{1}{mn}\sum_{(s,t)\epsilon s_{xy}} g(s,t)$	(2)
Median filter	$\hat{f}(x,y) = median_{(s,t)\epsilon s_{xy}}\{g(s,t)\}$	(3)
EnLee filter	$c_u = \sqrt{1/L}$ ،$c_i = \frac{Std.Dev^{1}}{mean} = \frac{S}{IM}$ ،$c_{max} = \sqrt{1 + 2/L}$ $w = e^{-dampfactor(\frac{c_i - c_u}{c_{max} - c_i})}$ ،$L = (\frac{mean}{\sigma})^2$ $\begin{Bmatrix} for\ c_i \le c_u \tilde{x} = \bar{y} \\ for\ c_u < c_i < c_{max} \tilde{x} = yw + \bar{y}(1-w) \\ for\ c_i \ge c_{max} \tilde{x} = y \end{Bmatrix}$	(4)
Kuan filter	$W = (\frac{1 - \frac{c_u^2}{c_i^2}}{1 + c_u^2})$ ،$c_u = \sqrt{1/L}$ ،$c_i = \frac{Std.Dev}{mean} = \frac{S}{IM}$ $R = I_c W + I_m(1 - W)$	(5)
Wiener2 filter	$\hat{f}(x,y) = \mu + \frac{\sigma^2 - v^2}{\sigma^2}(g(s,t) - \mu)$ V_2 =noise variance	(6)

[1]Standard deviation

Table 2. Several image quality assessment algorithms

Metrics	Equations	Relationship Number
MSE	$MSE = \frac{1}{MN}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left[f(m,n) - \hat{f}(m,n)\right]^2$	(7)
RMSE	$RMSE = \sqrt{MSE}$	(8)
PSNR	$PSNR = 10.log_{10}\left(\frac{255^2}{MSE}\right)$	(9)
Corr.	$Corr = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{(\sum_m \sum_n (A_{mn} - \bar{A})^2)(\sum_m \sum_n (B_{mn} - \bar{B})^2)}}$ $\bar{B} = mean2(B\ )and\ \ \bar{A} = mean2(A)$	(10)

2.3. Methods of statistical filtering

A number of methods have been proposed in section 2.3 to address the problem of removing speckle noise, while preserving the edge features in OCT images. According to Table 1, the Median filter calculates the median value in the local neighborhood of each pixel and the Kuan filter smoothes the image, without removing the edges or sharp features in the image [13, 14]. The grey-level value R for the smoothed pixel (I_c) is the central pixel in Kuan filter and I_m is the average intensity of pixels in the filter window [10, 15].

In EnLee filter, smoothing is done if the variance over an area is low or constant. Otherwise, if the variance is high (e.g., near the edges), smoothing is discarded. Parameter L (Number of looks) is used to describe the speckle noise variance in an image [15]. Also, Wiener2 function applies a Wiener filter (a type of linear filter) to an image adaptively, tailoring itself to the local image variance. When the variance is large, Wiener2 performs little smoothing, while more smoothing is achieved when the variance is small [9].

2.4. Methods of image quality assessment

In order to have a better understanding of the performance of statistical filters in section 2.3, it should be mentioned that several image quality assessment algorithms were employed in this study and the obtained results were compared in sections 3, 4 and 5 of the article. The most commonly used metrics for the evaluation of noise suppression and despeckled OCT image quality include PSNR, MSE, RMSE and Corr. Furthermore, to assess the run time of each filter, the elapsed time is considered. The definitions of these metrics are described in Table 2.

PSNR represents the ratio of the possible power of a signal and the power of corrupting noise, affecting the fidelity of its representation. Since many signals have a wide dynamic range, PSNR is usually expressed in terms of a logarithmic decibel scale [3]. PSNR is most easily defined via MSE [14]. MSE of an estimator is one of many ways to quantify the difference between values implied by an estimator and the true values of the quantity being estimated [14]. Also, RMSE is the square root of the mean square error, and quantifies the closeness between two images [16].

3. Results

In this study, to reduce speckle noise, statistical filters such as Mean, Median, Wiener2, EnLee and Kuan filters with different masks in speckle noise variances of 0.02, 0.2 and 0.59 were applied on OCT and test images. The results showed that Kuan and Enhanced Lee (EnLee) filters were more effective than other filters; they also increased image quality and maintained the features of OCT images. Moreover, the output was more favorable in Kuan filter, acting as an input filter for edge promotion.

3.1. Performance evaluation of statistical filters in different masks in low speckle noise variances

In Figure 2, which is the output of Table 3, EnLee and Kuan filters with 3×3 masks were more favorable in terms of PSNR and RMSE values, compared to other filters. In Figure 2, Graphs (a & b) show PSNR and RMSE values for each case with a variance of 0.02. Figure 5 is the summary of the performance of various statistical filters with a mask value of 3×3 (speckle noise variance of 0.02 was applied to OCT1 and OCT2 images). Graphs (c & d) in figure 2 show PSNR and RMSE values for each case with a speckle noise variance of 0.2. Figure 6 is the summary of the performance of various statistical filters (3×3) and EnLee filter with a mask value of 7×7 (speckle noise variance of 0.2 was applied to OCT3 and OCT4 images). Also, in Figure 2, EnLee and Kuan filters were more favorable in terms of PSNR and RMSE values, compared to other filters.

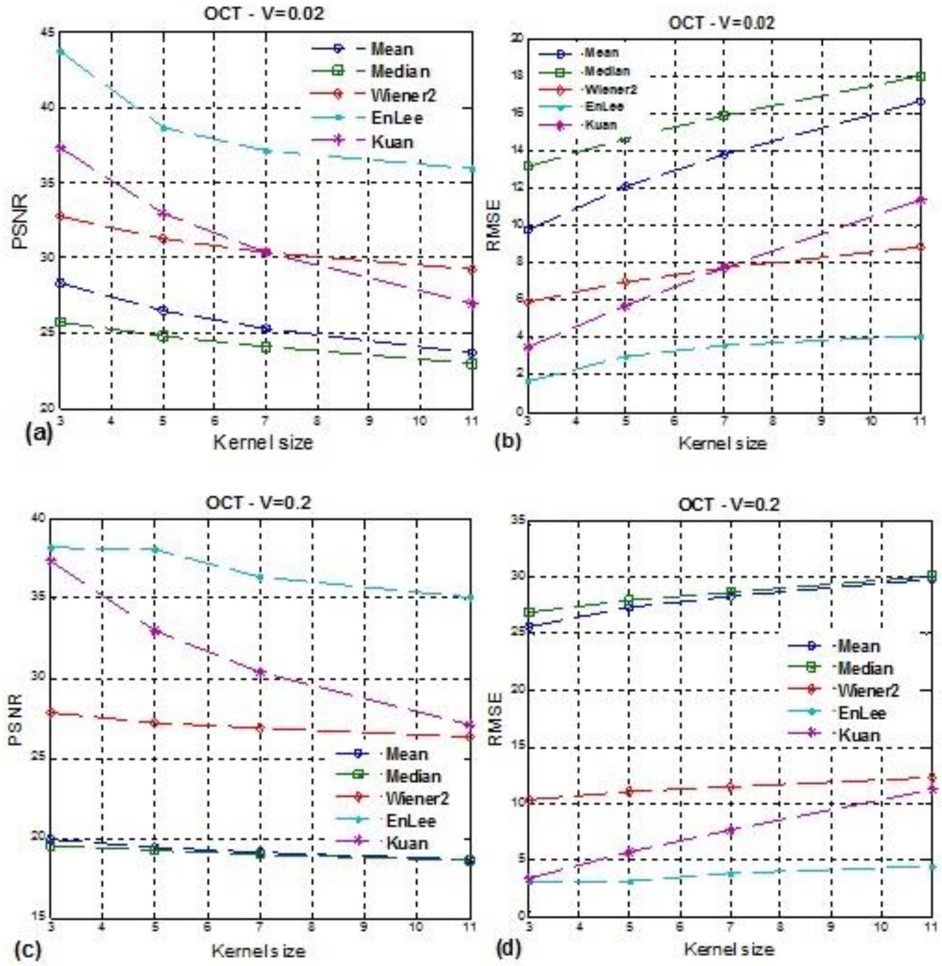

Figure 2. Performance of various statistical filters with different masks (3, 5, 7 & 11). Speckle noise variances of 0.02 and 0.2 were applied to the OCT1 image. Graphs (a) and (b) show PSNR and RMSE values for each case with speckle noise variance of 0.02. Graphs (c) and (d) show PSNR and RMSE values for each case with speckle noise variance of 0.2.

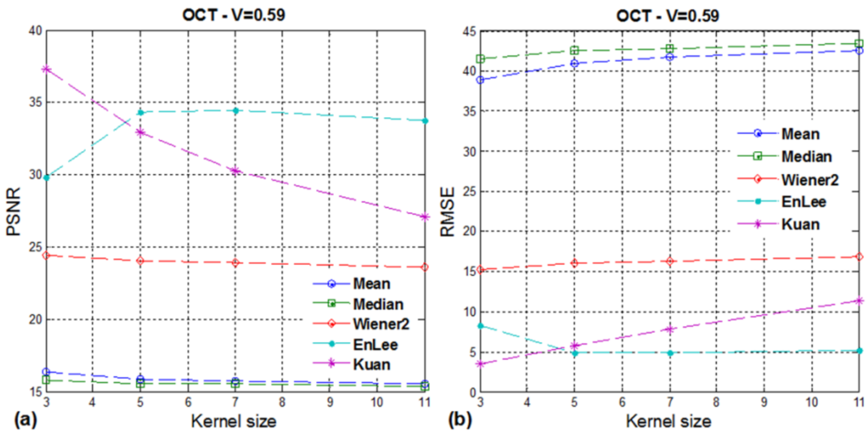

Figure 3. Performance of various statistical filters with different masks (3, 5, 7 & 11). Speckle noise variance of 0.59 was applied to the OCT1 image. Graphs (a) and (b) show PSNR and RMSE values for each case with speckle noise variance of 0.59.

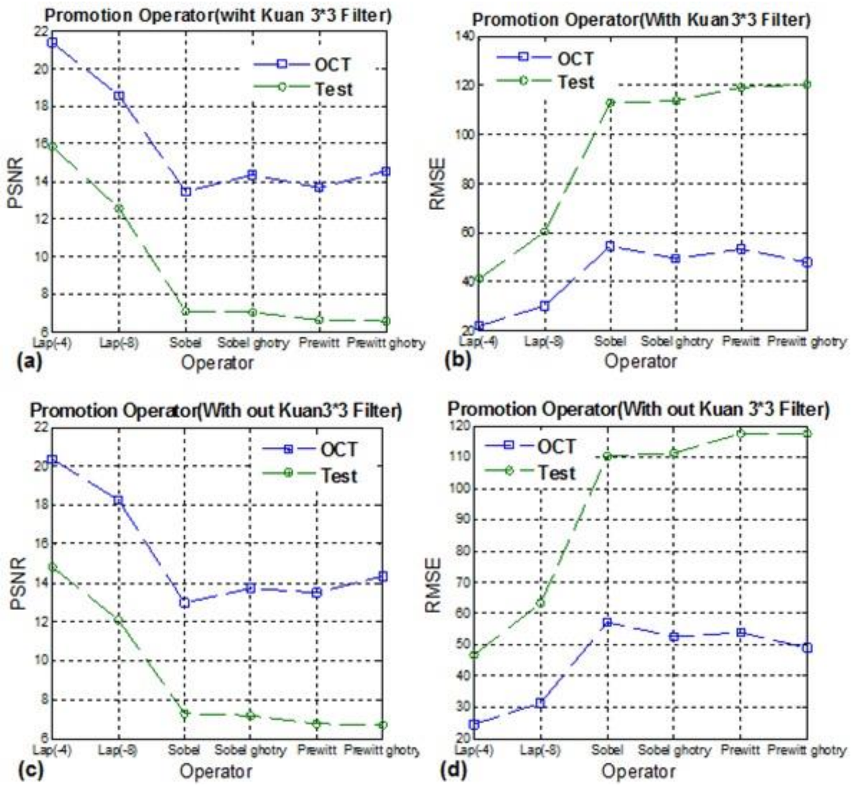

Figure 4. Performance of various edge promotion operators such as Laplacian, Prewitt, Sobel and Sobel & Prewitt masks to detect diagonal edges with speckle noise variance of 0.02, applied to OCT1 and test images. Graphs (a) and (b) show PSNR and RMSE values for each case with Kuan filter (3×3), used as the input filter. Graphs (c) and (d) show PSNR and RMSE values for each case without Kuan filter (3×3) as the input filter.

3.2. Performance evaluation of statistical filters in different masks in high speckle noise variances

Figure 3, which demonstrates the output of Table 4, presents a summary of the performance of various statistical filters with different masks (3, 5, 7 & 11). According to Figure 3, it can be seen that Kuan filter with a 3×3 mask is preferred to other filters with high PSNR values in a high speckle noise variance.

3.3. Assessments by applying edge promotion operators

In this study, after smoothing the image with a Kuan filter and eliminating the noise, the edge strength was determined. Figure 4, as the output of Table 5 presents a summary of the performance of various edge promotion operators such as Laplacian (-4 & -8), Prewitt, Sobel and Sobel & Prewitt masks in detecting diagonal edges with a speckle noise variance of 0.02, applied to OCT and test images.

According to figure 4a, which displays PSNR values in OCT1 and test images, use of Kuan filter (3×3) as an input filter results in more favorable outcomes in terms of higher PSNR values, compared to Figure 4(c), in which no filter has been used as the input for recovery.

Comparison of PSNR and RMSE values in edge promotion operators in Figures 4 & 7 indicates that Laplacian, Sobel and Prewitt masks were more effective in detecting diagonal edges and removing the noise.

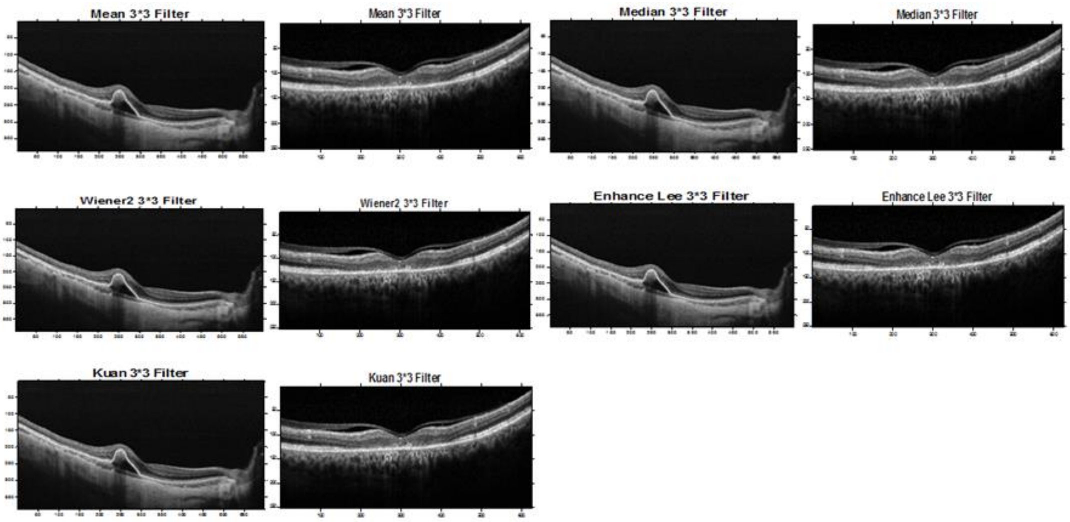

Figure 5. Summary of the performance of various statistical filters with a mask value of 3×3 (speckle noise variance of 0.02 was applied to OCT1 and OCT2 images)

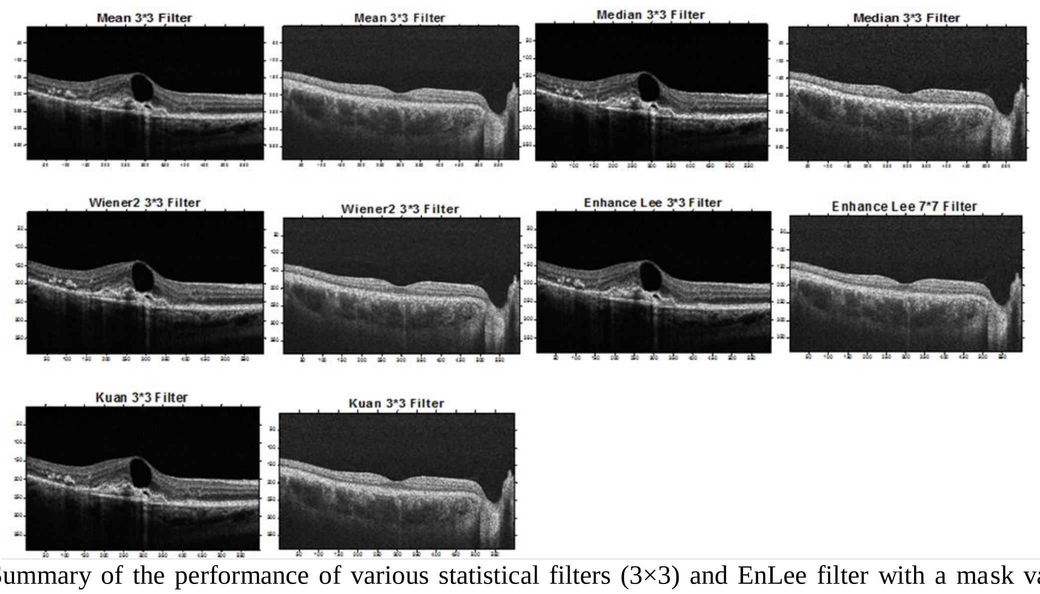

Figure 6. Summary of the performance of various statistical filters (3×3) and EnLee filter with a mask value of 7×7 (speckle noise variance of 0.2 was applied to OCT3 and OCT4 images

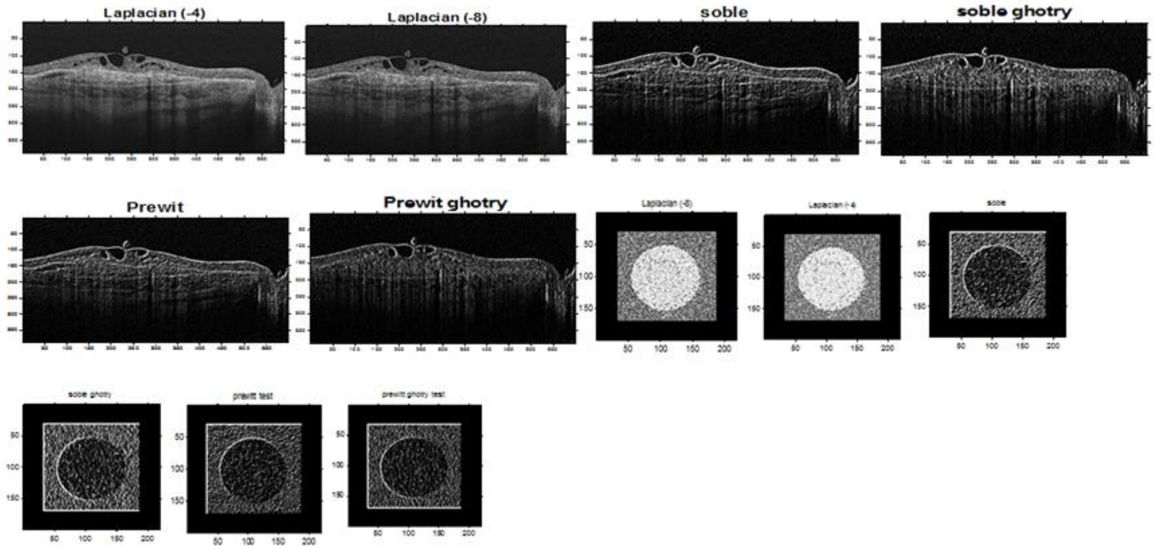

Figure 7. Summary of the performance of various edge promotion operators by adding Kuan filter (3×3) as an input filter (speckle noise variance of 0.02 was applied to OCT5 and test images)

Table 3: Results of image quality assessment in Mean, Median, Wiener2, EnLee and Kuan filters with masks (3) in speckle noise variance of 0.02

V=0.02	Filter	Mean	Median	Wiener2	EnLee	Kuan
Kernel size		3	3	3	3	3
PSNR	OCT1	28.3505	25.7329	32.7121	43.6735	37.2942
	OCT2	29.4012	26.6923	32.9835	42.4058	36.9353
MSE	OCT1	95.0671	173.6972	34.8234	2.7908	12.1243
	OCT2	74.6379	139.2662	32.7138	3.7368	13.1689
RMSE	OCT1	9.7502	13.1794	5.9011	1.6706	3.4820
	OCT2	8.6393	11.8011	5.7196	1.9331	3.6289
Corr	OCT1	0.9734	0.9835	0.9958	0.9995	0.9980
	OCT2	0.9800	0.9794	0.9942	0.9990	0.9963
Elapsed Time (sec)	OCT	6.4886	7.4279	9.8418	15.7035	14.6371

Table 4: Results of image quality assessment in Mean, Median, Wiener2, EnLee and Kuan filters with masks (3, 7) and speckle noise variance of 0.59

V=0. 59	Filter	Mean	Median	Wiener2	EnLee	Kuan
Kernel size		3	3	3	7	3
PSNR	OCT5	14.4445	13.8841	19.3433	38.0253	37.0360
	Test	11.7689	10.8838	17.7139	35.0959	40.2440
MSE	OCT5	2.3369e+003	2.6587e+003	756.3958	10.2458	12.8671
	Test	4.3271e+003	1.2080e+003	1.1008e+003	20.1135	6.1473
RMSE	OCT5	48.3411	51.5628	27.5027	3.2009	3.5871
	Test	65.7804	72.8335	33.1778	4.4848	2.4794
Corr	OCT5	0.6923	6573	9157	0.9995	0.9990
	Test	0.7919	7625	9553	0.9987	0.9999
Elapsed Time (sec)	OCT	6.3814	7.5354	9.9030	16.5576	13.3119

Table 5: Results of image quality assessment in various edge promotion operators by adding speckle noise variance of 0.02 to OCT and test images (the output of using and not using Kuan filter (3×3) as an input filter was compared)

V=0.02	Filter	Lap(-4)		Lap(-8)		Sobel	
acts		With Kuan3*3	Without Kuan3*3	With Kuan3*3	Without Kuan3*3	With Kuan3*3	Without Kuan3*3
PSNR	OCT	21.3965	20.3305	18.5971	18.2464	13.4387	12.9783
MSE	OCT	471.4411	602.5985	897.1880	973.7286	2.9459e+003	3.2753e+003
RMSE	OCT	21.7127	24.5479	29.9698	31.2046	54.2760	57.2300
Corr	OCT	0.9249	0.9050	0.8541	0.8470	0.5110	0.4811
Elapsed Time (sec)	OCT	11.6223	6.2673	11.7358	6.2676	11.7963	6.3881
PSNR	OCT	13.3226	13.7233	13.6366	13.4939	14.5707	14.3445
MSE	OCT	2.4034e+003	2.7590e+003	2.8146e+003	2.9087e+003	2.2699e+003	2.3913e+003
RMSE	OCT	49.0244	52.5260	53.0529	53.0321	47.6439	48.9008
Corr	OCT	0.5871	0.5472	0.4850	0.4575	0.5690	0.5303
Elapsed Time (sec)	OCT	11.9151	6.4019	11.8232	6.4398	11.6492	6.3579

4. Discussion

In this study, to reduce speckle noise, statistical filters such as Mean, Median, Wiener2, EnLee and Kuan filters with different masks in speckle noise variances of 0.02, 0.2 and 0.59 were applied on OCT and test images. Objective evaluation of both types of images was performed, using various image metrics such as PSNR, RMSE, Corr and elapsed time as the best options for filter retrieval (EnLee and Kuan filters). Kuan filter was selected as an input filter to enhance the edge of images in the speckle noise variance of 0.02. Finally, to analyze the output of edge enhancement, the ability of Kuan filter to avoid noise enhancement was reviewed, and various image metrics were examined.

In Figure 2, which is the output of Table 3, EnLee and Kuan filters with 3×3 masks were more favorable in terms of PSNR and RMSE values, compared to other filters. In Figure 2, performance of various statistical filters with different masks (3, 5, 7 &11) is demonstrated. Speckle noise variances of 0.02 and 0.2 were applied only for OCT1 image. Graphs (a) and (b) show PSNR and RMSE values for each case with a variance of 0.02.

According to Figure 2(a), which demonstrates PSNR values in OCT1 image, EnLee filter with a 3×3 mask was preferred to other filters with high PSNR values (by as much as 43.6735). EnLee and Kuan filters with different masks were also applied. Figure 2(b), which displays RMSE values in OCT1 image, shows low RMSE in EnLee filter with a 3×3 mask (by as much as 1.5431). Figure 5 is the summary of the performance of various statistical filters with a mask value of 3×3 (speckle noise variance of 0.02 was applied to OCT1 and OCT2 images).

Also, in Figure 2, EnLee and Kuan filters were more favorable in terms of PSNR and RMSE values, compared to other filters. Graphs (c) and (d) show PSNR and RMSE values for each case with a speckle noise variance of 0.2. According to figures 2(c) and 2(d), displaying PSNR values in OCT1 image, it can be seen that EnLee and Kuan filters with different masks were superior to other filters. Figure 6 is the summary of the performance of various statistical filters (3×3) and EnLee filter with a mask value of 7×7 (speckle noise variance of 0.2 was applied to OCT3 and OCT4 images).

Figure 3, which demonstrates the output of Table 4, presents a summary of the performance of various statistical filters with different masks (3, 5, 7 & 11). According to Figure 3(a), which displays PSNR values in OCT1 image, it can be seen that Kuan filter with a 3×3 mask is preferred to other filters with high PSNR values (by as much as 37.2850). Moreover, EnLee and Kuan filters with different masks were applied. In Figure 3(b), which displays RMSE values in OCT1 image, low RMSE value in the Kuan filter with a 3×3 mask is indicative of the superiority of Kuan filter in a high speckle noise variance.

Edge detection is a difficult task in noisy images, since both noise and edges contain high-frequency contents. The first step in edge detection is to filter out any noise in the OCT image before trying to locate and detect the edges. In this study, after smoothing the image with a Kuan filter and eliminating the noise, the edge strength was determined.

Figure 4 & 7, as the output of Table 5 presents a summary of the performance of various edge promotion operators such as Laplacian (-4 & -8), Prewitt, Sobel and Sobel & Prewitt masks in detecting diagonal edges with a speckle noise variance of 0.02, applied to OCT and test images. Graphs (a) and (b) in figure 4 show PSNR and RMSE values for each case with the Kuan filter (3×3), used as an input filter. Also, graphs (c) and (d) show PSNR and RMSE values for each case, without using this filter as the input filter.

According to figure 4a, which displays PSNR values in OCT1 and test images, use of Kuan filter (3×3) as an input filter results in more favorable outcomes in terms of higher PSNR values, compared to Figure 4(c), in which no filter has been used as the input for recovery. In graphs 4(b) and 4(d), displaying RMSE values in OCT1 and test images, similar results were reported.

Comparison of PSNR and RMSE values in edge promotion operators in Figure 4 & 7 indicates that Laplacian, Sobel and Prewitt masks were more effective in detecting diagonal edges and removing the noise.

5. Conclusion

The obtained results suggest that although the elapsed time in using EnLee and Kuan filters, as provided in tables 3 & 4 , was longer, EnLee and Kuan filters had more favorable impacts on speckle noise reduction in high and low variances in terms of PSNR, RMSE and Corr. values, compared to Mean, Median and Wiener2 filters. This would also contribute to maintaining and increasing the accuracy of image resolution around tissues in OCT images. Also, since these filters can preserve the edges, they are more desirable as input filters for improving the edges in OCT images.

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