Evaluation of Speckle Noise Reduction and Feature Enhancement in Prolapsed Mitral Valve Leaflet Echocardiography

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Abstract. Rheumatic heart disease has a substantial impact on morbidity and mortality for both men and women in developing countries. It is a complication of autoimmune phenomenon known as acute rheumatic fever in response to group A streptococcus bacteria. It often causes damage to valves and lacks its functionality. Initial manifestations of prolapsed valves are evident in echocardiography in the form of valve bulging, commissural fusion and restricted leaflet motion. However, these echocardiogram images are inevitably degraded by multiplicative noise known as speckle noise at the time of image acquisition and transmission. Hence despeckling is of vital importance for enhancing ultrasound image quality. In this paper, a comparative analysis of well established despeckling filters compiled for speckle suppression and feature enhancement has been performed. In addition to this, the performance of these filters is validated using different quantitative metrics. The experimental result shows that feature enhanced Fast Non-Local Means (FNLM) filter outperforms other state-of-art filtering techniques in the aspect of higher PSNR value and preserves structural similarity in terms of SSIM value near to unity. In conclusion, the preprocessing intends to suppress speckle noise and enhancing perceived visual quality that aids for further development of virtual cardiac model.

1. Introduction

The wide accessibility and advancement of digital technology assist the medical experts to make the diagnosis of the disease more precisely, for instance, the X-rays, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Ultrasound (US) and Positron Emission Tomography (PET) imaging. Among these diagnosis-aid technologies, ultrasound turns into a primary modality in recent years due to its noninvasive, faster and benign environment [1][2]. Cardiac ultrasound, also termed as echocardiography remains the best modality choice for the diagnosis of cardiovascular diseases such as Rheumatic heart disease (RHD). It is regarded as the leading cause of death representing 60 to 65% of all global deaths. Although any cardiac valve may be affected, mitral valve is the most commonly affected valve, resulting in mitral stenosis or mitral regurgitation [3]. Stenosis occurs when the mitral valve opening is narrowed whereas regurgitation occurs when the mitral leaflets does not seal properly, inducing the blood to flow backward [4]. However, diagnosis of mitral valve abnormalities in echocardiogram videos is still an open challenging task. Speckle noise may be encountered in these videos due to scattering of ultrasound signals from the small rapidly moving structures within the soft tissues. Furthermore granular pattern of speckle limit the post-processing
techniques such as valve segmentation and motion tracking [5]. Speckle noise is modeled as a multiplicative noise based on the following equation (1).

\[ p(x, y) = q(x, y) \ast n_{mul}(x, y) + n_{add}(x, y) \]  

Where \( p(x, y) \) is the speckle corrupted image, \( q(x, y) \) is the original ultrasound image, \( n_{mul}(x, y) \) and \( n_{add}(x, y) \) are the multiplicative and additive components [6]. Since the additive component of speckle noise is very small it can be ignored as given in equation (2)

\[ p(x, y) = q(x, y) \ast n_{mul}(x, y) \]  

Over the years, plenty of filtering techniques with better noise suppression capabilities have been introduced. The main aim of this study is concerning a thorough review of various classical filters such as fast non-local means filter, Gaussian filter, Median filter, Crimmins and Lee filter for removing speckle noise followed by contrast-limited adaptive histogram equalization (CLAHE) method to yield a desired level of feature enhancement in cardiac ultrasound images.

The rest of the paper is summarized as follows. Section II addresses the brief summary of well known speckle denoising approaches. Section III describes the framework for speckle suppression and feature enhancement of cardiac echo videos. Section IV deals with experimental results and analysis. Section V concludes the work summary and highlights the future directions.

2. Background

In the past decades, lots of filtering techniques have been contributed for medical ultrasound image despeckling. In general, these filters are based on spatial and frequency domain. Mohamed Yaseen Jabarulla et al. [7] they proposed a study based on spatial filters such as kuan, Frost, Mean, Median and Speckle Reducing Anisotropic Diffusion (SRAD) filters. Their results showed that denoising effect and overall visual quality of hepatic cyst ultrasound images is enhanced using SRAD filter with a PSNR value of 31.11 dB.

In [8], Mrunal N. Annadate et al. recommend a Hybrid Median Filter (HMF) which is a modification of median filter for feature preservation on fetal ultrasound videos. Despite of using three step ranking, this HMF filter failed to tackle the problem of computational complexity.

P M Shankar [9] analyzed the behavior of denoising based on local statistics in B mode ultrasound images. They have proposed a maximum likelihood adaptive filter depends on the variation of window size. The performance level of this filter preserves the edges in echoic target, but declining fine details in low frequency area.

In [10] Sumit Kushwaha et.al presented an approach for quantitative analysis of four state-of-the-art filters, namely Median, Lee, Frost and SRAD filters on B-mode Ultrasound images of human kidney. They suggested quantitative comparisons on the basis of PSNR and SSIM with varying kernel levels and iterations. The Experimental results have been proven that SRAD and Median filters are the remarkable filters for despeckling.

The proposed idea of non linear anisotropic diffusion filtering based on partial differential equation (PDE) has been incorporated by Sumit Kushwaha [11]. For the experimental analysis purpose, eight clinical B-Mode Ultrasound images of human liver from different patients have considered. The denoising behavior of existing speckle suppression filters such as Malik Filter, LEE Filter, Frost Filter and Anisotropic Diffusion for Memory Based on Speckle Statistics Filter (ADMBSS) has been compared with a proposed approach in terms of PSNR. The authors claimed that the proposed method revealed satisfactory results in comparison with standalone filters.

Adil H. Khan et.al [12] proposed a novel schur based approach where the ultrasound image is segmented into a small sequence of overlapping segments to obtain orthogonal vectors. A non empty subset of orthogonal vectors with maximum Eigen values has been selected for the maximum filtration of speckle noise. The proposed approach has been examined on both simulated and real ultrasound images of kidney, foetal neck, musculo skeletal nerve and lymph node and found outperforming with benchmarking techniques such as homomorphic wavelet despeckling (HWDS), Wiener, Frost and Gamma. Overall performance of the proposed schur method can be verified as the prominent method.
mainly on the basis of parameters PSNR (peak signal-to-noise ratio), SNR (signal-to-noise ratio), Alpha and CNR (carrier-to-noise ratio) with optimal resolution. However, speckle noise is either inefficiently suppressed or higher degree of distortion is relatively included into despeckled images. Hence, previous studies provide the realization of speckle suppression and feature enhancement to preserve the quality of the echocardiographic images.

3. Overview of Speckle Reduction and Feature Enhancement Framework
Preprocessing improves the interpretability of information in digital images for human perception. The core objectives of preprocessing deployed in this research work are noise reduction and contrast-limited adaptive histogram equalization (CLAHE) as depicted in Figure 1. Typical echocardiography videos used in our analysis were obtained from publicly available dataset echocardia (www.echocardia.com) [13]. A total of 10 mitral valve echo videos of subjects was collected from four standard perspective views, parasternal long axis (PLAX) view, parasternal short axis (PSAX) view, apical 4-chamber (A4C) view and esophageal view. The echo videos of patients affirmed with pathology of either mitral stenosis or mitral regurgitation, which was in MP4 format are reviewed for this study.

The obtained echo videos were sampled by a default sampling rate (25 frames per second) to individual frames and from each video ten successive frames were incorporated in the analysis. Furthermore, as all the subject’s protected health information (PHI) must be anonymize to secure the patient’s privacy, optical character recognition (OCR) was used to de-identify the clinical metadata annotations from each frame dealt with patient identification, date of image acquisition and so on [14]. Text within the image was identified using this OCR technique based on non-uniform contrast background. Suspected clinical PHI in a bounding box was redacted by reassigning with lowest pixel value typically black which would result in anonymized echo images. After de-identification of sensitive data, corrupted images were obtained by addition of speckle noise with variance 0.001. Further, speckle noise has been significantly suppressed using different filters with 3x3 mask size. Finally, the denoising behavior of aforementioned filters is further improved by using a CLAHE method with clip limit value one.

![Figure 1. Framework for speckle denoising and feature enhancement](image)

3.1. Speckle Reduction Filters
This section addresses speckle reduction filters and their mathematical implementations in detailed fashion.

3.1.1. Lee Filter
The Lee filter [15][16] adopts a linear multiplicative model based on minimum mean square error (MMSE). It is a patch based processing and every pixel in the noisy image is processed individually within the moving window or the kernel. It reduces the speckle noise by replacing the center pixel of a kernel with the average intensities of the window. This method can be implemented based on the following equation
\[ D_{i,j} = \bar{Y} + W(C_p - \bar{Y}) \]  

(3)

Where \( D_{i,j} \) is the despeckled image, \( \bar{Y} \) is the mean of the pixel values in the kernel, \( C_p \) is the center pixel of the kernel and weighting function \( W \) is given by

\[ W = \frac{\rho^2}{\rho^2 + \sigma^2} \]  

(4)

Where \( \rho^2 \) is the variance of pixel values in the kernel and \( \sigma^2 \) is the variance of the pixel values in the reference image.

3.1.2. Median Filter

Median Filter [17][18] which is used in our approach is a non linear filter based on order statistics. The idea of median filter is to replace the noisy value of the center pixel with a median of its pixel neighborhood. Prior to process the speckled image with this filter, at first all the pixels in the window must be sorted in numerical order. It is estimated using the mathematical equation as follows:

\[ \hat{f}(u,v) = \text{med}(f(u-i,v-j)), i,j \in K \]  

(5)

Where \( f(u,v) \) is the speckle corrupted original image, \( \hat{f}(u,v) \) is despeckled output image, \( K \) is two dimensional mask or kernel. Typically, size of a kernel is often selected as odd numbers and lowest window size needs to be chosen to reduce the time complexity of denoising.

3.1.3. Crimmins Speckle Filtering

The concept of geometric despecle filter introduced by Crimmins [19] uses complementary hulling noise reduction technique. These filters are non-linear in the sense that it is either incrementing value of dark pixel or decrementing light pixel by comparing the intensity of the pixel with the 4 set of its neighbors (North to South, East to West, Northeast to Southwest and Northwest to Southeast). The denoising behavior of these filters smoothen the edges of ultrasound images as well as it is iteratively used over filtered image to reduce noise level.

3.1.4. Gaussian Filter

Gaussian filter [20] is a convolution based linear filter that replaces individual higher value pixels by a weighted average of pixels on the periphery. It suppresses speckle noise based on Gaussian distribution.

The 2D Gaussian filtering with a mean value zero and standard deviation as one is given in equation (6)

\[ G(x,y) = \frac{1}{2\pi \sigma^2} e^{-\frac{(x^2+y^2)}{2\sigma^2}} \]  

(6)

Where \( \sigma \) represents standard deviation and \( x \) and \( y \) are the coordinates of an image.

3.1.5. Fast Non-Local Means (NLM) filter

Non-Local Means is a patch based denoising method in which a target pixel is compared with similar patches and restored the particular target pixel by averaging the group of neighborhood pixels. This traditional method makes use of Gaussian Euclidean distance to find out cues of similar patches. The performance of this pixel wise approach deteriorates depends on the assumption that all the pixels can be linked to other pixels with self-similarities. The problem of computational complexity due to this pixel-wise method is minimized by using block-wise method, namely fast non-local means filtering [21]. Consider the image region over \( \Omega \) as blocks \( b_{i,j} \) and performing the same pixel-wise approach on each block. Let \( \text{NLM}(b_{i,j}) \) be the restored block on the image I and \( w(i,j) \) be a weighted average of all pixels in block \( b_{i,j} \). It can be formulated as in equation (7)

\[ \text{NLM}(b_{i,j}) = \sum_{b_{i,j} \in \Omega} w(i,j) f(b_{i,j}) \]  

(7)

When setting the argument fast-mode as true, uniform spatial weighting is employed to compute Euclidean distance between patches. Otherwise, Gaussian Euclidean distance is applied over the patches. Overall, it provides edge preservation and noise suppression that would be degraded by other denoising methods [22].
3.2. Contrast-Limited Adaptive Histogram Equalization (CLAHE)
Contrast-Limited Adaptive Histogram Equalization (CLAHE) method significantly enhancing low contrast of ultrasound frames at good scale. The method partitions the image into non-overlapping tiles that contain an \( M \) number of pixels using desired tile size. After that Histogram is computed for each tile, part of the histogram bin that exceeds the corresponding clip limit is clipped. Furthermore, the amount of clipped pixels is distributed by any one of the distribution functions, namely uniform, Rayleigh and Exponential [23]. Finally, transform function is computed for neighboring tiles and interpolation method is adopted for binding the transform function to obtain the enhanced image. In our methodology, uniform distribution in combination with Bilinear Interpolation [24][25] is applied over the pixels to obtain desired contrast levels as shown in Figure 3.

4. Experimental Results and Analysis
The framework for the echocardiography video speckle suppression using denoising filters combined with contrast-limited adaptive histogram equalization improves the overall visual quality of video frames. In this section, qualitative analysis is performed with prolapsed mitral valve echocardiography images. To evaluate the performance, the original echo images are corrupted with noise variance 0.001 and window size 3x3 is selected to filter noisy cardiac images. Visual comparison of all speckle suppression filters that constitutes four cardiac views is presented in Figure 2. Out of all filters, the fast non-local mean filter excels over the other filtered output in terms of visual quality. Figure 3 shows the output of CLAHE method based on a uniform distribution. The output generated using fast non-local mean filter provides an acceptable level of contrast enhancement with clip limit value 1.
Figure 2. Comparison of various despeckling filters. (a)-(d) Four Perspective echo viewpoints of mitral valve frames with noise variance 0.001. Left to right: parasternal short axis, parasternal long axis, esophageal view, Apical four chamber view, (a)-(d) Noisy images, (e)-(h) Denoised images using Lee filter, (i)-(l) Denoised images using median filter, (m)-(p) Denoised results of Crimmins, (q)-(t) Denoised images using Gaussian, (u)-(x) Denoised results of Fast non-local means.
Table 1, 2 and 3 presents resultant performance analysis of four echocardiography views based on metrics such as mean squared error (MSE), peak signal-to-noise ratio (PSNR), The Structural Similarity Index (SSIM), Universal Quality Index (UQI), Pixel-based Visual Information Fidelity (VIFP), Noise Quality Measure (NQM). From the observing overall performance of Table 4, it is evident that denoising effect achieved by fast non-local means filter is more than up to par with higher PSNR and low MSE values, though the behavior of Gaussian also retained similar higher values. Meanwhile Figure 4 depicts an average graphical variation of speckle suppression results as measured by different metrics.

Table 1. Cardiac view based performance analysis in terms of PSNR and SSIM.

|        | PLAX       | PSAX       | A4C         | Eso phageal |
|--------|------------|------------|-------------|-------------|
| PSNR   | 0.64022    | 0.641035   | 0.646836    | 0.597907    |
| SSIM   | 0.832306   | 0.898397   | 0.852189    | 0.844974    |

Table 2. Cardiac view based performance analysis in terms of UQI and MSE.

|        | PLAX       | PSAX       | A4C         | Eso phageal |
|--------|------------|------------|-------------|-------------|
| UQI    | 0.723068   | 0.778664   | 0.633661    | 0.977909    |
| MSE    | 0.931058   | 0.944226   | 0.989767    | 0.989523    |

Figure 3. Speckle-filtered contrast enhanced echo frames using CLAHE algorithm on different filters. First row shows the original images from four perspective echo view points, second row shows the speckle-filtered contrast enhanced output with Lee and Median filter, third row and fourth row depicts the output with Crimmins and Gaussian, fifth row outputs the enhanced features and edges with fast non-local mean filter.
Table 3. Cardiac view based performance analysis in terms of VIFP and NQM.

|       | VIFP     | NQM     |
|-------|----------|---------|
|       | Crimmins | FastN1  | Gaussian | Lee | Median | Crimmins | FastN1  | Gaussian | Lee | Median |
| PLAX  | 0.64022  | 0.832306| 0.845355 | 0.312752 | 31.59618 | 42.98828 | 44.0803 | 24.8329795 | 38.34751 |
| PSAX  | 0.641035 | 0.898397| 0.861226 | 0.377294 | 32.35361 | 42.92463 | 44.21692 | 23.4753697 | 38.43324 |
| A4C   | 0.64836  | 0.852189| 0.843328 | 0.345792 | 31.7508  | 43.54755 | 44.38987 | 26.9631126 | 38.37024 |
| Esophageal | 0.597907 | 0.844974| 0.869521 | 0.264345 | 31.02127 | 46.0564  | 42.19617 | 19.9239791 | 36.84979 |

Table 4. Overall Performance Analysis of Various Filters.

|       | PSNR     | SSIM     | UQI      | MSE       | VIFP     | NQM     |
|-------|----------|----------|----------|-----------|----------|---------|
|       | Crimmins | Fast Non-Local\textsuperscript{a} | Gaussian | Lee | Median | Crimmins | Fast Non-Local\textsuperscript{a} | Gaussian | Lee | Median |
| PSNR  | 39.17681 | 44.90212 | 44.89687 | 27.44004 | 33.10179 | 0.907547 | 0.995197 | 0.963644 | 0.959198 | 0.951919 | 0.778526 | 0.993741 | 0.959198 | 0.951919 | 0.856967 | 0.854858 | 0.856967 | 0.854858 | 43.87922 | 43.72082 |
| SSIM  | 0.907547 | 0.995197 | 0.993741 | 0.959198 | 0.951919 | 0.778526 | 0.995197 | 0.963644 | 0.959198 | 0.951919 | 0.778526 | 0.995197 | 0.963644 | 0.959198 | 0.951919 | 0.856967 | 0.854858 | 0.854858 | 0.854858 | 31.78653 | 31.78653 |
| UQI   | 0.778526 | 0.995197 | 0.993741 | 0.959198 | 0.951919 | 0.778526 | 0.995197 | 0.963644 | 0.959198 | 0.951919 | 0.778526 | 0.995197 | 0.963644 | 0.959198 | 0.951919 | 0.856967 | 0.854858 | 0.854858 | 0.854858 | 31.78653 | 31.78653 |
| MSE   | 0.254237 | 0.208265 | 2.175865  | 47.102636 | 33.87942 | 0.907547 | 0.995197 | 0.963644 | 0.959198 | 0.951919 | 0.778526 | 0.995197 | 0.963644 | 0.959198 | 0.951919 | 0.856967 | 0.854858 | 0.854858 | 0.854858 | 31.78653 | 31.78653 |
| VIFP  | 0.63151  | 0.856967 | 0.854858 | 0.325046 | 0.621853 | 0.63151  | 0.856967 | 0.854858 | 0.325046 | 0.621853 | 0.63151  | 0.856967 | 0.854858 | 0.325046 | 0.621853 | 0.63151  | 0.856967 | 0.854858 | 0.325046 | 0.621853 | 31.78653 |
| NQM   | 31.78653 | 43.87922 | 43.72082 | 23.79886 | 38.0002  | 31.78653 | 43.87922 | 43.72082 | 23.79886 | 38.0002  | 31.78653 | 43.87922 | 43.72082 | 23.79886 | 38.0002  | 31.78653 | 43.87922 | 43.72082 | 23.79886 | 38.0002  | 31.78653 |

\textsuperscript{a}Best performance metrics are highlighted as bold

Figure 4. Average variations of resultant image quality as measured by different metrics

5. Conclusion and Future Directions

This paper has explored the complete pipeline for speckle suppression and feature enhancement of mitral valve echocardiography videos. The processing pipeline used various denoising filters and limits over amplification of noise using contrast adaptive feature enhancement (CLAHE) algorithms. The presented work proved that Fast non-local means filter outperforms the other filtering techniques in terms of resultant image visual quality and structural edge preservation. Besides, quantitative analysis is also evaluated in terms of different quality metrics. The experimental analysis suggested that CLAHE based
on the uniform distribution in combination with bilinear interpolation highlight the features with denoising. Future work can be extended with various file formats and noise levels to enhance overall efficiency as well, which can be further directed towards the development of virtual cardiac model.

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