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# Echocardiographic image denoising using extreme total variation bilateral filter

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ABSTRACT

The transthoracic echocardiographic (TTE) images used to assess cardiac health are inherent with speckle noise, making it very difficult for accurate abnormality diagnosis. To address this issue, a novel speckle reduction known as extreme total variation bilateral (ETVB) filter is proposed in this paper. The regularizer term of total variation (TV) method is replaced with the bilateral (BL) term in the proposed ETVB filter along with the prior term. The true information is incorporated in the algorithm using Bayesian inference and probability density function. Applications of gradient projection based restoration methods are also analyzed for speckle noise reduction. Denoising characteristics are evaluated in terms of 15 image quality metrics along with visual quality. The performance of proposed ETVB filter is compared with 30 existing despeckling techniques. Exhaustive result analysis reveals that the proposed ETVB filter is superior in terms of edge and texture preservation. The focal points of result analysis are edge, structure and texture preservation along with visual outlook. Edge and structure preservation are measured using beta metric, figure of merit and structure similarity index. The values of $\beta$, FoM and SSIM are markedly enhanced using proposed filtering scheme in comparison to other total variation based methods.



## 1. Introduction

Echocardiography, an ultrasound based imaging modality is generally used in the assessment of valvular diseases such as regurgitation, and stenosis of aortic valve [1,2]. The cross sectional images in various views are employed for locating the cardiac abnormalities and in study of the consequences of regurgitation on cardiac chambers [1–3]. The rapid advancements in transducers, image acquisition and image processing techniques, the quality of echocardiographic has improved drastically [4]. But the issue using cross sectional images is they have higher amount of speckle noise present in them [3]. Echocardiography is an ultrasound based technique, which is non-invasive, less expensive, easily portable to the bed side of the patient and ready to use, needing no special environment to work upon. The other side of echocardiographic images is they are low in contrast; poor visibility, operator dependency, artifacts, shadowing, reverberation and speckle noise making it extremely difficult for accurate and consistent measurement of cardiac size and shape [2–4].

The number of research papers on ultrasound image analysis especially on preprocessing and segmentation has drastically increased, which reflects the need and urgency to further enhance the quality of ultrasound images [3,5–9]. Various types of filtering techniques based on various principles such as multiscale [3,5–8,10], diffusion [3,6,7,11], nonlocal means [7,12,13], total variation [14–18], bilateral [19–22], and fuzzy techniques [23,24] are available for noise reduction. The despeckling applications of total variation based are not extensively worked out and usage is less reported for echocardiographic images. The most recent review papers on ultrasound images [3,5–9] do not mention applications of TV based denoising methods. This paper presents a study on the applications of total variation based noise reduction integrated with bilateral filter and prior information for despeckling of TTE images acquired in various views. The concept of total variation (TV) is being employed in applications such as image denoising, deblurring, inpainting and various others, ever since the idea proposed by Rudin, Osher and Fatemi (ROF) in the year 1992 [15,18,25,26]. It is currently an active area of research in the field of image preprocessing, image restoration and reconstruction. The issues of concern, during the usage of TV in noise reduction are loss of contrast, loss of geometry and staircase effects, under various circumstances [18,25,26]. To address these issues, modified versions of TV and new techniques have come into existence,

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these include techniques such as anisotropic total variation (ATV), isotropic total variation (ITV) [14], adaptive fidelity total variation (AFTV) [16], duality based gradient projection algorithms [17], total variation as local filter [18], replacement of $L^2$ norm with $L^1$ norm in the fidelity term [26], and others. Zhu et al. [17] studied the applications of duality based gradient projection (GP) restoration algorithms including Barzilai–Boorwein (BB) methods. The performances were analyzed in terms of tolerance, number of iterations and CPU time. This paper analyses the applications of all methods of [17] for speckle noise reduction. Ertas et al. [25] combined denoising features of total variation and nonlocal means for reduction of artifacts in 3D iterative image reconstruction. TV was employed for removing background noise while NLM for reduction of out-of-focus blur. The performances were analyzed using structural similarity (SSIM) index, root mean square error (RMSE) and signal to noise ratio (SNR). The concept of edge and texture preservation are not considered in [25].

The objective of this paper is also to study the denoising performance ROF total variation [15] and its variants such as AFTV [16], ATV, ITV [14] along with proposed ETVB filtering scheme, duality based gradient projection algorithms [17], DsF [6], Fourier filters [5], NLM based filters [12,13] and fast bilateral filter [20] in terms of image quality metrics. A brief description of denoising techniques is available in Section 2 along with the proposed ETVB filter. The methods of evaluating the filtering techniques, description of image quality metrics and clinical database used, and method of acquiring data are very briefly described in Section 3. Results are analyzed in Section 4 followed by conclusions in Section 5.

## 2. Denoising techniques

The intensity variations within an organ or tissue are not as prominent as at the boundaries. Rapid variations are noticed at the boundary walls of organs and tissues. Therefore, minimizing total variation of a medical image may significantly improve the quality by preserving the edges and smoothing the image [25]. Total variation based denoising is effective in suppressing noise but often fails to preserve small details like texture information [25]. To address this issue, extreme total variation bilateral (ETVB) based filtering scheme is proposed and analyzed in this paper.

### 2.1. Bilateral filter

Bilateral is a non-linear, weighted averaging based filtering technique. It is popularly known for smoothing of images while preserving the edges. The image processing applications of bilateral filter have drastically increased since its naming as Bilateral by Tomasi Manduchi in the year 1998 [19,21,22,27]. One of the basic and important applications of bilateral filter is image denoising. It is also used in applications such as tone mapping, contrast enhancement, image fusion, compression of artifacts, mesh smoothing, image interpolation, optical flow mapping, depth map estimation, medical imaging, and video enhancement.

The popularity of bilateral filters can be attributed to (1) simplicity in formulation; (2) efficiency dictated by selection of only two parameters; and (3) high computational speed [19,27]. It works by estimating weighted average of neighboring pixels. The basic theme incorporated in the working of bilateral filter is a pixel will have influence another pixel if it is located in its nearby vicinity and has similar value [22,27]. The bilateral filter [21] is defined as

$BL[f]_p = 1/W_p \sum_{q \in S} G_{\sigma_s}(\|p-q\|) \times G_{\sigma_r}\left(\left\|f_p - f_q\right\|\right) \times f_p$, where $W_p$ is the normalization factor and it is computed as $W_p = G_{\sigma_s}(\|p-q\|) \times G_{\sigma_r}\left(\left\|f_p - f_q\right\|\right)$. The parameters $\sigma_s$ and $\sigma_r$ along with the window size dictate the amount of denoising which can be achieved using Bilateral filter [21]. The weighted average are computed based on the range and distance Gaussian kernels with $G_{\sigma_r}$ as the range Gaussian and $G_{\sigma_s}$ is the spatial Gaussian. The spatial Gaussian decreases the influence of distant pixels whereas the range Gaussian helps in reducing the influence, when the intensity values are different. The final weight is product of temporal (spatial) and distant weights [21,22,27]. Kornprobst et al. has recommended a linear dependence defined as $\sigma_r = 1.95\sigma_n$, where $\sigma_n$ represents the local noise level [19,27]. The optimal value of $\sigma_s$ is relatively insensitive to noise present compared to $\sigma_r$ and it may be chosen as constant as somewhere around 1.8. The kernels are normalized, the sum of coefficients is 1, and centre pixel value of the kernel will be largest and kernel may have any form.

The input image is being used for the estimation of spatial and range weights, followed by multiplication of these values resulting in edge preserved and smooth image. Initially, texture map and block discontinuity maps are generated. The distant component is estimated using texture map and range component is estimated using block discontinuity maps. Each of the pixel value is substituted by weighted average of its neighbor. Each pixel is penalized by two components i.e. spatial component penalize distant pixel and range component penalizes pixel with different intensity values. Integration of range and spatial components ensure that only similar pixels in the neighborhood contribute towards the final pixel values. Thus, the bilateral filters delivers despeckled image with contours and edges well preserved.

### 2.2. Duality based algorithms for total variation

The applications of GP algorithms, variants of GP algorithm, were studied by Zhu et al. [17] for reduction of Gaussian noise in terms of computational burden, number of iterations and tolerance. The denoising applications of the following algorithms are studied and analyzed in this paper along with the proposed ETVB filtering scheme: Chambolle algorithm, Chan-Golub-Mulet (CGM) algorithm, gradient projection with constant length (GPCL), GP with backtracking line search (GPLS), sequential quadratic programming with spectral BB(SQPBB), primal-dual hybrid gradient (PDHG), GP with BB (GPBB), GP with cyclic BB (GPCBB), GPPB with safeguarding (GPPBsafe), GPPB with monotone version of BB step length (GPPBNM), GP with adaptive BB (GPABB) and GPBB, SQPBB, GPABB with different number of cycles such as M2 for two cycles, M3 for three cycles. The values of various parameters in implementation of duality based GP algorithms are based on the analysis and discussion in [17], constant fidelity term is 0.045, fixed step length is 0.248, and maximum number of iterations is 5 in all the implementations in this paper. The complete details of duality based GP algorithms are available in [17] and the MATLAB code provided by authors of [17] are being used.

### 2.3. Despeckling filters (DsF)

DsFlsmv (Despeckling filter-local statistics mean and variance) is a first order statistics based filtering technique, works based on statistical values such as the mean and the variance of neighborhood [6,9]. The image quality metrics of DsFlsmv filter are estimated by setting the number of iteration equal to 2 and moving window size as 5 × 5. Despeckling filter-local statistics minimum speckle index (DsFlsminsc) is known as homogenous mask area filtering [6,9]. The wiener filter results in best restored image in terms of square error. It is abbreviated as DsFwiener (despeckling filter-wiener). DsFgf4d (despeckling filter-geometric in four direction) [6,9], works by increasing or decreasing the values of neighborhood pixels depending on their relative values. The following parameters are considered for DsFad (despeckling filter- anisotropic) filter: number of iterations = 10 to 60, diffusion constant = 30, rate