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Despeckle Filtering Toolbox for Medical Ultrasound Video

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ABSTRACT

Ultrasound medical video has the potential in differentiating between normal and abnormal tissue and structure. Ultrasound imaging is used in border identification and texture characterisation of the atherosclerotic carotid plaque in the common carotid artery (CCA), the identification and measurement of the intima-media thickness (IMT) and the lumen diameter that are very important in the assessment of cardiovascular disease. However, visual perception is reduced by speckle noise affecting the quality of ultrasound B-mode imaging. Noise reduction is therefore essential for increasing the visual quality or as a pre-processing step for further automated analysis, such as the video segmentation of the IMT and the atherosclerotic carotid plaque in ultrasound video sequences. In order to facilitate this analysis, the authors have developed a video analysis software toolbox based on MATLAB® that uses video despeckling, texture analysis and image quality evaluation techniques to automate the pre-processing and complement the disease evaluation in ultrasound CCA videos. The proposed software, which is based on a graphical user interface (GUI), incorporates video normalisation, 4 different despeckle filtering techniques (DsFlsmv, DsFhmedian, DsFkuwahara and DsFsradi), 65 texture features, 11 quantitative video quality metrics and objective video quality evaluation. The software was validated on 10 ultrasound videos of the CCA, by comparing its results with quantitative visual analysis performed by two medical experts. It was shown that the filters DsFlsmv, and DsFhmedian improved video quality perception (based on the expert's assessment and the video quality metrics). It is anticipated that the system could help the physician in the assessment of cardiovascular video analysis. However, exhaustive evaluation of the despeckle filtering toolbox has to be carried out by more experts on more videos.

Keywords: Common Carotid Artery (CCA), Despeckling, Speckle, Texture Analysis, Ultrasound, Video

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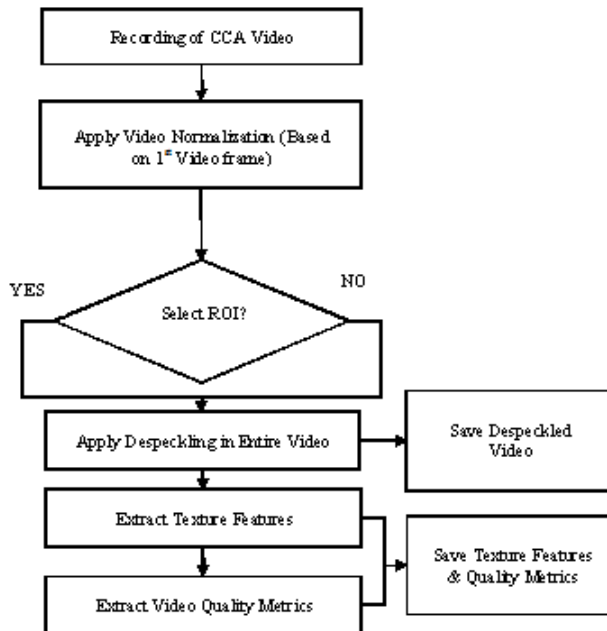
INTRODUCTION

Despite significant progress made in the last few years and the vast technological advancements in image and video processing, there are a number of factors that negatively influence the visual quality of images and videos, and hinder the automated analysis (Wang, 2004). These include video acquisition technologies, imperfect instruments, natural phenomena, transmission errors, and coding artifacts, which degrade the quality of video data by inducing noise (Loizou, 2008; Loizou, 2012b). Ultrasound imaging and video is a non-invasive powerful diagnostic tool in medicine, but it is degraded by a form of multiplicative noise (speckle), which makes the observation difficult (Loizou, 2005; Loizou, 2008). It is therefore of interest for the research community to investigate and apply new video despeckle filtering techniques that can increase the visual perception evaluation and further automate video analysis, thus improving the final diagnosis. These techniques are usually incorporated into integrated software medical image/video processing applications.

We propose in this study an integrated software toolbox (see also Figure 1 and Figure 2) for ultrasound video despeckling that can be utilized in video analysis. The present work is an extended version of a conference paper presented in the BIBE conference (Loizou, 2012b), where ultrasound video despeckling of the common carotid artery (CCA) was proposed. In order to quantitatively evaluate the proposed software system we applied different video despeckle filtering techniques and investigated their performance on 10 ultrasound videos of the CCA. The despeckling filtering techniques and the integrated software toolbox were also evaluated through visual perception, performed by two vascular experts, a cardiovascular surgeon, and a neurovascular specialist, before and after despeckle filtering. The video despeckle filtering techniques were further evaluated through a number of texture features and video quality metrics, which were extracted from the original and the despeckled videos.

There are a number of studies reported in the literature, where ultrasound image medical software systems have been introduced. An overview of these systems is given in Table 1. The systems tabulated have been grouped under freeware, and commercial. Loizou and Pattichis (2008) published a monograph on despeckle filtering that was accompanied with a despeckle filtering toolbox for ultrasound imaging of the CCA, whereas, in this paper an ultrasound video despeckle filtering toolbox is introduced. Both systems can be downloaded from <http://www.cs.ucy.ac.cy/medinfo/>. The commercial imaging systems cover the measurement of intima-media thickness (IMT), as well as the plaque texture characterization. For IMT measurement, several systems are available in the market, those that are included in the widely known commercial ultrasound machines (Esaote S.p.A, Philips Electronic Ltd) as well as the ones that can be purchased as stand-alone software systems (Segment™, Atheroedge™, Royal Perth IMT software and M'Ath®). More specifically, in Davis et al. (2010), the RF-QIMT & RF-QAS integrated patented commercial imaging software system (Esaote S.p.A, Florence, Italy) for the segmentation of the intima-media complex (IMC) was proposed and evaluated on 635 subjects. The Segment™ software used also by Phillips Electronics Ltd, was presented by Heiberg et al. (2010) and is suitable for cardiovascular image analysis. Molinari and co-workers (2011) patented the architecture of an automated strategy, which segments the lumen-intima and media adventitia borders in 2D ultrasound images. This system was classified under a class of patented AtheroEdge™ systems by Global Biomedical Technologies, Inc, CA, USA. A commercial IMT software system tool that can be used to measure the IMT and the lumen diameter in ultrasound images, and image sequences of the CCA was developed by the Royal Perth Hospital, Australia. Moreover, a software system from M'Ath® Intelligent Medical Technologies, Argenteuil, France was presented for the segmentation of the IMT from 2D ultrasound images of the CCA. Finally,

Figure 1. Flowchart analysis of despeckle filtering toolbox for ultrasound video



in Kyriakou et al., (2007), a commercialized software system for the manual delineation, and automated image normalization and texture

analysis of the atherosclerotic carotid plaque in ultrasound images of the CCA was presented.

The structure of the rest of the paper is as follows: In section 2, the theoretical concepts

Figure 2. The graphical user interface (GUI) of the proposed despeckle filtering toolbox for ultrasound video. The following components are shown: original video display, original video settings, despeckled video display, despeckled video settings (filter settings), number of frames for video despeckling, texture analysis and quality analysis.

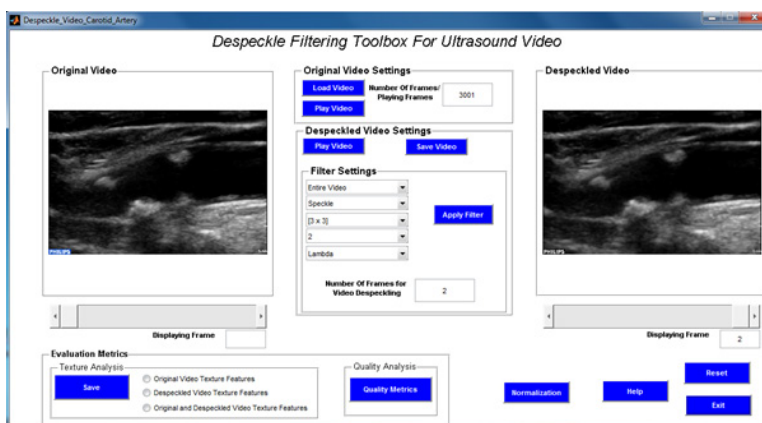


Table 1. An overview of selected ultrasound common carotid artery imaging and video analysis software systems

Principal Investigator	Year	Method	2D/3D	Software Platform	N
Freeware-Despeckling					
Loizou	2008	Despeckle Image Filtering	2D	Matlab®	440
Loizou	2012	Despeckle Video Filtering	2D	Matlab®	10
Commercial Imaging Systems-Intima Media Thickness Measurement					
Esaote S.p.A RF-QIMT&RF-QAS	2009	IMT Measurement and Quality Arterial Stiffness ⁺	2D	ART.LAB	635
Segment™, Phillips Electronics Ltd	2010	Cardiovascular Image Analysis	2D/3D	Windows/Matlab®	-
Global Biomedical Technologies AtheroEdge™	2011	IMT Measurement	2D	Matlab®	500
Royal Perth Hospital	2011	IMT Software	2D	Windows	-
M'Ath® Intelligent Medical Technologies	2012	IMT Measurement	2D	Windows	-
Commercial Imaging Systems-Plaque Segmentation and Texture Characterization					
Kyriakou	2007	Normalization and Plaque Texture Analysis	2D	Matlab®	440

N: Number of cases investigated. +: Based on the radio frequency signal.

of the proposed video despeckle filters are presented. In section 3 we provide information for the materials and methods used in this study, while in section 4 we present the results of this study. Sections 5 and 6 present a discussion in relation to previous results from other studies, and the concluding remarks respectively.

Image/Video Despeckle Filters

In this section, the theoretical background for the following four video despeckle filtering methods is introduced: a) linear despeckle filter (DsFlsmv), b) hybrid median filter (DsFhmedian), c) nonlinear filter (DsFkuwahara), and d) speckle reducing anisotropic diffusion (DsFsrad) filtering. Further algorithmic implementation details and coding can be found in (Loizou, 2008). These filters were applied to each video frame: a) for the whole video frame, and b) for a region of interest (ROI) in each video. The number of iterations, the filtering window size and other filtering parameters that

are used for each despeckle filtering method were tuned based, on the subjective despeckled video evaluation by two medical experts (see also section 3E).

Linear Despeckle Filter (DsFlsmv)

The filters of this type utilize the first order statistics such as the variance and the mean of a pixel neighbourhood and may be described by a multiplicative noise model (Loizou, 2005; Loizou, 2006; Lee, 1980). Hence the algorithms in this class may be traced back to the following equation:

$$f_{i,j} = \bar{g} + k_{i,j}(g_{i,j} - \bar{g}) \quad (1)$$

where $f_{i,j}$, is the estimated noise-free pixel value, $g_{i,j}$, is the noisy pixel value in the moving window, \bar{g} , is the local mean value of an $N_1 \times N_2$ region surrounding and including

pixel $g_{i,j}$, $k_{i,j}$ is a weighting factor, with $k \in [0,1]$, and i,j are the pixel coordinates. The factor $k_{i,j}$, is a function of the local statistics in a moving window and is defined (Loizou, 2005; Loizou, 2006; Lee, 1980) as:

$$k_{i,j} = \frac{(1 - \bar{g}^2 \sigma^2)}{(\sigma^2 + \sigma_n^2)} \quad (2)$$

The values σ^2 , and σ_n^2 , represent the variance in the moving window and the variance of noise in the whole video frame respectively. The noise variance may be calculated for the logarithmically compressed frame by computing the average noise variance over a number of windows with dimensions considerably larger than the filtering window (Loizou, 2005; Loizou, 2006; Lee, 1980). The moving window size for the despeckle filter DsFlsmv can be selected from 3x3 up to 16x16 and the number of iterations applied to each video frame from 1 to 20.

Hybrid Median Filtering (DsFhmedian)

DsFhmedian was introduced in (Nieminen, 1987) and computes the median of the outputs generated by median filtering with three different windows (cross shape window, x-shape window and normal window). A 5x5 size moving window is used with a selectable number of iterations applied to each video frame ranging from 1 to 20.

Nonlinear Filtering (DsFkuwahara)

The DsFkuwahara is an 1D filter operating in a 5x5 pixel neighborhood by searching for the most homogenous neighborhood area around each pixel (Kuwahara, 1976; Loizou, 2008). The middle pixel of the 1x5 neighborhood is then substituted with the median gray level of the 1x5 mask. The filter is iteratively applied a selectable (from 1 to 20) times on the video frame.

Speckle Reducing Anisotropic Diffusion Filtering (DsFsrad)

Speckle reducing anisotropic diffusion is described in Yongjian (2002). It is based on setting the conduction coefficient in the diffusion equation using the local frame gradient and the frame Laplacian. The DsFsrad speckle reducing anisotropic diffusion filter in Yongjian (2002) uses two seemingly different methods, namely the Lee (Lee, 1980) and the Frost diffusion filters (Frost, 1982). A more general updated function for the output image by extending the PDE versions of the despeckle filter is in Yongjian (2002):

$$f_{i,j} = g_{i,j} + \frac{1}{\eta_s} \text{div}(c_{srad}(|\nabla g|) \nabla g_{i,j}) \quad (3)$$

where η_s is the size of the filtering window. The diffusion coefficient for the speckle anisotropic diffusion, $c_{srad}(|\nabla g|)$, is given in Yongjian (2002):

$$c_{srad}(|\nabla g|) = \frac{\frac{1}{2} |\nabla g_{i,j}|^2 - \frac{1}{16} (\nabla^2 g_{i,j})^2}{(g_{i,j} + \frac{1}{4} \nabla^2 g_{i,j})^2} \quad (4)$$

It is required that $c_{srad}(|\nabla g|) \geq 0$. The above instantaneous coefficient of variation combines a normalized gradient magnitude operator and a normalized Laplacian operator to act like an edge detector for speckle images. High relative gradient magnitude and low relative Laplacian indicates an edge. The DsFsrad filter utilizes speckle reducing anisotropic diffusion after (3) with the diffusion coefficient, $c_{srad}(|\nabla g|)$ in (4) (Yongjian, 2002). The coefficient of variation for the DsFsrad filter can be selected from 0.01 up to 0.1 and the number of iterations from 1 to 200.

Despeckle Filtering Toolbox For Ultrasound Video

The proposed integrated software toolbox for ultrasound video despeckling, implements procedures for loading video files of most popular standards (see also Figure 1). The video analysis usually starts with a definition of an ROI in the first video frame where despeckle filtering will be applied in a frame by frame basis for the whole video sequence. There are 65 different texture features and six video quality metrics that are extracted and evaluated by comparing the original and despeckled videos.

Figure 1 presents a flowchart analysis of the proposed integrated video despeckling software system, where the different modules of the software are outlined. In Figure 2 we present the graphical user interface (GUI) of the proposed system. The video despeckling software can be downloaded as an executable code from <http://www.cs.ucy.ac.cy/medinfo/>.

Recording and Display of Ultrasound Videos

A total of 10 B-mode longitudinal ultrasound videos of the CCA bifurcation from women and men of 40 years or older were recorded (see Figure 3 and Figure 4) representing different types of atherosclerotic plaque formation (Type I to Type IV; Loizou, 2005; Loizou, 2008) with irregular geometry typically found in this blood vessel. The videos were acquired using the ATL HDI-5000 ultrasound scanner (Advanced Technology Laboratories, Seattle, USA) (A Philips Medical Company, 2001) and were recorded digitally on a magneto optical drive, with a resolution of 576x768 pixels with 256 gray levels, and having a frame rate of 100 frames/sec. The ATL HDI-5000 ultrasound scanner is equipped with a 256-element fine pitch high-resolution 50-mm linear array, a multi-element ultrasound scan head with an extended operating frequency range of 5–12 MHz and it offers real spatial compound imaging. B-mode scan settings were adjusted at 170 dB, so that the maximum dynamic range was used with a linear post-processing curve. In order to ensure that

a linear-post-processing curve is used, these settings were pre-selected (by selecting the appropriate start-up presets from the software) and were included in the part of the start-up settings of the ultrasound scanner. The position of the probe was adjusted so that the ultrasonic beam was vertical to the artery wall. The time gain compensation (TGC) curve was adjusted (gently sloping) to produce uniform intensity of echoes on the screen, but it was vertical in the lumen of the artery where attenuation in blood was minimal so that echogenicity of the far wall was the same as that of the near wall. The overall gain was set so that the appearance of the plaque was assessed to be optimal, and slight noise appeared within the lumen. It was then decreased so that at least some areas in the lumen appeared to be free of noise (black).

All video frames were manually resolution-normalized at 16.66 pixels/mm. This was carried out to overcome the small variations in the number of pixels per mm of image depth (i.e. for deeply situated carotid arteries, image depth was increased and therefore digital image spatial resolution would have decreased) and in order to maintain uniformity in the digital image spatial resolution (Kyriakou, 2005). The videos were recorded from 6 asymptomatic subjects and from 4 symptomatic subjects at risk of atherosclerosis, who have already developed clinical symptoms, such as a stroke or a transient ischemic attack (TIA). The video despeckling methods can be performed for a selected time interval, covering the cardiac cycles of interest or under investigation.

Ultrasound Video Normalization

Brightness adjustments of ultrasound videos (see Figure 3 and Figure 4) can be carried out based on the method introduced in Elatrozy (1998), which improves image compatibility by reducing the variability introduced by different gain settings, different operators, different equipment, and facilitates ultrasound tissue comparability (Kyriakou, 2005). Algebraic (linear) scaling of the first video frame is manually performed by linearly adjusting the image so that the median gray level value of the blood

Figure 3. Examples of despeckle filtering on a video frame of a CCA video acquired from a male symptomatic subject at the age of 62 with 40% stenosis and a plaque at the far wall of the CCA, for the whole image frame in the left column, and on an ROI (including the plaque (shown in b)), in the right column for: a), b) original, c), d) DsFlsmv, e), f) DsFhmedian, g), h) DsFkuwahara, and i), j) DsFsrad. The automated plaque segmentations are shown in all examples.

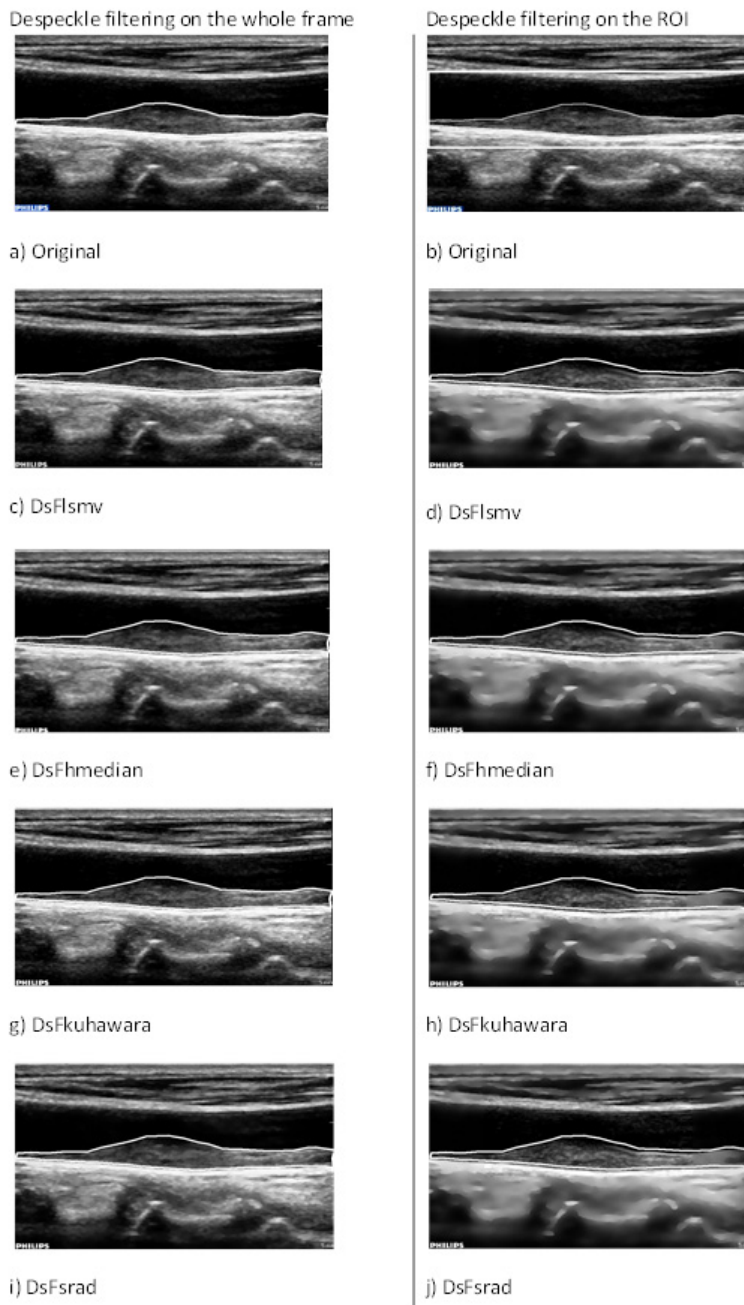
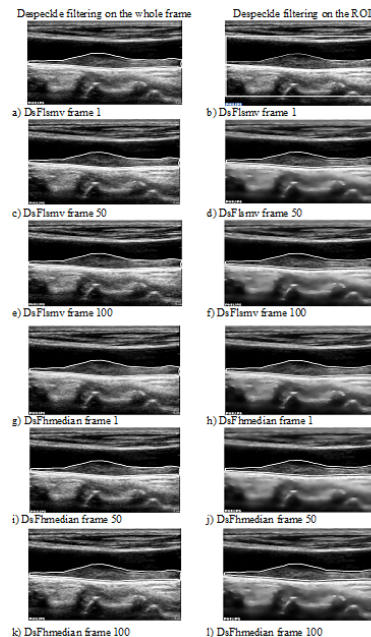


Figure 4. Examples of despeckle filtering with the filter DsFlsmv (a-f) and DsFhmedian (g-l) on a video of the CCA, acquired from a male symptomatic subject at the age of 62, with 40% stenosis and a plaque at the far wall of the CCA, on frames 1, 50 and 100 for the whole image frame in the left column, and on an ROI (shown in b)), in the right column. The automated plaque segmentations are shown in all examples.



was 0-5, and the median gray level of the adventitia (artery wall) was 180-190 (Elatrozy, 1998; Nicolaides, 2003). The scale of the gray level of the video frames ranged from 0-255. Thus the brightness of all pixels in the video frame is readjusted according to the linear scale defined by selecting the two reference regions. The subsequent frames of the video are then automatically normalized based on the selection of the first frame. The operator of the proposed software tool cannot intervene in the normalization process of subsequent frames. It is noted that a key point to maintaining a high reproducibility was to ensure that the ultrasound beam was at right angles to the adventitia, adventitia was visible adjacent to the plaque and that for image normalization a standard sample consisting of the half of the width of the brightest area of adventitia was obtained.

Despeckle Filtering

Despeckle filtering can be applied either to the whole frame or to an ROI selected by the user (see Figure 3 and Figure 4, where both are applied in the whole video). In the latter case, where the user of the system is interested only in the selected ROI, the area outside the ROI can be blurred using the DsFsrads filter with 100 iterations and a coefficient of variation 0.05 (or using another filter). It should be noted that the blurring is applied outside of the ROI if the user of the system is not interested to subjectively evaluate this area. The input parameters of the despeckle filters DsFlsmv, DsFhmedian, DsFkuwahara and DsFsrads can be selected by the user. These are the size of the sliding moving window and the number of iterations, as well as the coefficient of variation that is required for the DsFsrads filter.

Texture Feature Analysis

Texture provides useful information for the characterization of the atherosclerotic carotid plaque in both images and videos of the CCA (Christodoulou, 2003). The proposed system (see Figure 1 and Figure 2) is able to extract a total of 65 different texture features both from the original and the despeckled video frames as follows (Christodoulou, 2003):

1. Statistical Features (SF): 1) Mean, 2) Median, 3) Variance (σ^2), 4) Skewness (σ^3), and 5) Kurtosis (σ^4).
2. Spatial Gray Level Dependence Matrices (SGLDM) as proposed by (Haralick, 1973): 1) Angular second moment (ASM), 2) Contrast, 3) Correlation, 4) Sum of squares variance (SOSV), 5) Inverse difference moment (IDM), 6) Sum average (SA), 7) Sum variance (SV), 8) Sum entropy (SE), 9) Entropy, 10) Difference variance (DV), 11) Difference entropy (DE), 12), and 13) Information measures of correlation (IMC). For a chosen distance d (in this work $d=1$ was used) and for angles $\theta = 0^\circ, 45^\circ, 90^\circ$, and 135° , we computed four values for each of the above texture measures. Each feature was computed using a distance of one pixel. Then for each feature the mean values and the range of values were computed, and were used as two different feature sets.
3. Gray Level Difference Statistics (GLDS) (Weszka, 1976): 1) Homogeneity, 2) Contrast, 3) Energy, 4) Entropy, and 5) Mean. The above features were calculated for displacements $\delta=(0, 1), (1, 1), (1, 0), (1, -1)$, where $\delta \equiv (\Delta x, \Delta y)$, and their mean values were taken.
4. Neighborhood Gray Tone Difference Matrix (NGTDM) (Amadasun, 1989): 1) Coarseness, 2) Contrast, 3) Busyness, 4) Complexity, and 5) Strength.
5. Statistical Feature Matrix (SFM) (Wu, 1992): 1) Coarseness, 2) Contrast, 3) Periodicity, and 4) Roughness.
6. Laws Texture Energy Measures (LTEM) (Wu, 1992): 1) LL-texture energy from LL kernel, 2) EE-texture energy from EE-kernel, 3) SS-texture energy from SS-kernel, 4) LE-average texture energy from LE and EL kernels, 5) ES-average texture energy from ES and SE kernels, and 6) LS-average texture energy from LS and SL kernels.
7. Fractal Dimension Texture Analysis (FDTA) (Wu, 1992): The Hurst coefficients for dimensions 4, 3 and 2 were computed.
8. Fourier Power Spectrum (FPS) (Wu, 1992): 1) radial sum, and 2) angular sum.
9. Shape Parameters: 1) X-coordinate maximum length, 2) Y-coordinate maximum length, 3) area, 4) perimeter, 5) perimeter²/area, 6) eccentricity, 7) equivalence diameter, 8) major axis length, 9) minor axis length, 10) centroid, 11) convex area, and 12) orientation.

Visual Evaluation by Experts

In order to objectively evaluate the proposed system, the 10 ultrasound videos of the CCA were inspected visually after video normalization and speckle reduction filtering (see Section 3B and Section 3C) by two vascular experts, a cardiovascular surgeon, and a neurovascular specialist before and after despeckle filtering, using MATLAB® software developed by our group. For each case, the original and the normalized despeckled videos (despeckled with filters DsFlsmv, DsFhmedian, DsFkuwahara, DsFsrاد) were presented blindly at random to the two experts. The experts were asked to assign a score in the one to ten scale corresponding to low and high subjective visual perception criteria. Ten was given to a video with the best visual perception. Therefore the maximum score for a filter is 100, if the expert assigned the score of 10 for all the 10 videos. The experts were allowed to give equal scores to more than one video in each case. For each class and for each filter the average score was computed. The two experts evaluated the area around the distal CCA, 2-3 cm before the

bifurcation and the bifurcation around the plaque borders. It should also be noted that the scoring system used in this work presupposes an a priori knowledge of the range of the quality of the videos, therefore the two experts surveyed in random order all 10 videos before proceeding to the scoring procedure.

Video Quality Metrics

Objective video quality assessment is an emerging area of active research (Varghese, 2008). This is very different than image quality assessment that has seen significant growth and success over the last 10 years. Important video quality metrics, which are also investigated in this study include: a) structural similarity index (SSI), b) visual signal-to-noise ratio (VSNR), c) information fidelity (IFC), d) noise quality measure (NQM), e) weighted signal-to-noise ratio (WSNR) and f) Peak signal-to-noise ratio (RSNR). We refer to (Merix_mux software) for algorithmic details and implementation. The above video quality metrics were calculated from the original and the despeckled video frames.

RESULTS

Examples Using the Despeckle Filtering Toolbox for Ultrasound Video

The performance of the proposed video despeckle filtering toolbox was evaluated after video normalization and despeckle filtering using visual perception evaluation, texture features, and image quality evaluation metrics. Figure 3 presents the frame 100 of the video from a symptomatic subject for the original and the despeckled frames with filters DsFlsmv, DsFhmedian, DsFkuwahara, and DsFsrad when applied to the whole frame (left column) and on an ROI selected by the user of the system (right column) respectively. The automated plaque segmentations performed by an integrated system proposed in Loizou (2007b) are also shown in the images. The filters DsFlsmv and

DsFhmedian smoothed the video frame without destroying subtle details. Figure 4 presents the application of the DsFlsmv (see Figure 4 a-f) and the DsFhmedian (see Figure 4 g-l) despeckle filters, which showed best performance (see Tables 2-4), on consecutive video frames (1, 50 and 100) of a symptomatic subject, for the cases where the filtering was applied on the whole video frame (see left column of Figure 4) and on an ROI selected by the user (see right column of Figure 4).

Texture Feature Analysis

As texture features data are not normally distributed, the Wilcoxon rank sum test (Altman, 1991), which calculates the difference between the sum of the ranks of two independent samples, may be used in order to identify if for each set of texture features a significant difference (S) or not (NS) exists between the extracted features between the original and the despeckled frames, with a confidence level of 95% ($p < 0.05$).

Table 2 presents the results of selected texture features (from the SF and SGLDM feature sets, see section 3D) that showed significance difference after despeckle filtering ($p < 0.05$). The features were extracted from the original video frame and the despeckled video frames for the whole video frame and the ROI, for all 10 videos investigated in this study. These features were the median, variance, IDM, entropy, SV, DE, coarseness, complexity and roughness. It is shown that the filters DsFlsmv and DsFhmedian comparatively preserved the features median, variance and entropy but increased coarseness. It should be noted that these findings cannot be compared with the results presented in references Loizou (2005), and Loizou (2006), as the texture features in these two studies were computed for the DsFlsmv despeckled plaque images (and not the ROIs as defined in this study).

Visual Evaluation by Experts

Table 3 presents the average results of the visual evaluation of the original and despeckled videos made by the two experts, a cardiovascular

Table 2. Texture features (mean \pm sd), that showed significant difference (using the wilcoxon rank sum test at $p<0.05$) after despeckle filtering, for all 10 videos of the cca extracted from the original and the despeckled videos from the whole video and the roi (-/-).

Features	original	DsFlsmv	DsFhmedian	DsFkuwahara	DsFsrاد
Statistical Features					
Median	43 \pm 14 / 23 \pm 17	43 \pm 14 / 28 \pm 18	43 \pm 14 / 26 \pm 12	42 \pm 14 / 26 \pm 17	43 \pm 14 / 26 \pm 14
Variance	54 \pm 7 / 58 \pm 8	53 \pm 6 / 58 \pm 9	54 \pm 6 / 58 \pm 8	55 \pm 8 / 59 \pm 9	54 \pm 6 / 62 \pm 8
Spatial Gray Level Dependence Matrix					
IDM	0.27 \pm 0.07 / 0.29 \pm 0.14	0.29 \pm 0.07 / 0.075 \pm 0.08	0.39 \pm 0.05 / 0.078 \pm 0.08	0.41 \pm 0.07 / 0.083 \pm 0.088	0.38 \pm 0.06 / 0.034 \pm 0.038
Entropy	7.8 \pm 0.5 / 7.0 \pm 0.96	7.7 \pm 0.4 / 6.7 \pm 0.9	7.5 \pm 0.4 / 6.6 \pm 0.9	7.5 \pm 0.6 / 6.6 \pm 1.1	7.4 \pm 0.5 / 7.01 \pm 0.8
Sum Average	0.27 \pm 0.09 / 0.91 \pm 0.71	0.42 \pm 0.16 / 0.38 \pm 0.2	0.37 \pm 0.16 / 0.53 \pm 0.44	0.38 \pm 0.17 / 0.39 \pm 0.19	0.26 \pm 0.11 / 0.52 \pm 0.37
Sum Variance	104 \pm 37.66 / 205 \pm 199	109 \pm 52 / 57 \pm 28	90 \pm 27 / 112 \pm 115	135 \pm 42 / 117 \pm 46	105 \pm 53 / 95 \pm 83
DE	0.74 \pm 0.15 / 0.9 \pm 0.2	0.74 \pm 0.12 / 0.77 \pm 0.15	0.69 \pm 0.12 / 0.74 \pm 0.13	0.7 \pm 0.11 / 0.72 \pm 0.1	0.61 \pm 0.09 / 0.56 \pm 0.16
Neighborhood Gray Level Matrix (NGLM)					
Coarseness	38 \pm 7 / 61 \pm 11	93 \pm 13 / 110 \pm 22	52 \pm 10 / 84 \pm 21	37 \pm 4 / 55 \pm 12	54 \pm 22 / 33 \pm 18
Complexity (x1000)	74.33 \pm 12.81 / 44.16 \pm 14.8	49.4 \pm 6.5 / 29.5 \pm 9.5	59.5 \pm 7.4 / 36.7 \pm 13.1	68.6 \pm 12.1 / 69.6 \pm 21.8	62.7 \pm 11.3 / 67.9 \pm 19.1
Statistical Features Matrix (SFM)					
Roughness	2.21 \pm 0.014 / 2.16 \pm 0.02	2.14 \pm 0.012 / 2.11 \pm 0.01	2.11 \pm 0.013 / 2.11 \pm 0.02	2.15 \pm 0.01 / 2.13 \pm 0.01	2.18 \pm 0.03 / 2.28 \pm 0.09

IQR: Inter-qrtile range, SOV: Sum of squares variance,, ASM: Angular second moment, IDM: Inverse difference moment, DE: Difference entropy

surgeon and a neurovascular specialist. The evaluation was performed on both the whole despeckle video frame as well as to the ROI, where both methods gave similar visual evaluation scorings. We present the overall average percentage (%) score assigned by both experts for each filter and the filter ranking. It is shown in Table 3 that marginally the best video despeckle filter is the DsFlsmv with a score of 74%, followed by the filter DsFhmedian and DsFkuwahara with scores of 73% and 71% respectively. The filter DsFsrاد gave poorer performance with an average score of 56%.

Video Quality Metrics

Table 4 tabulates selected video quality metrics between the original and the despeckled videos for the whole frame filtering and when the filtering was applied on an ROI. It is clearly shown that the despeckle filter DsFlsmv performs better in terms of quality evaluation for the metrics WSNR, VSNR, SSI, IFC and NQM, when applied on the whole frame. Moreover, all the investigated evaluation metrics gave better results when the DsFlsmv was applied only on the ROI, followed by the DsFhmedian.

Table 4. Video quality metrics (mean \pm sd) for all 10 videos of the cca extracted between the original and the despeckled videos from the whole video and the roi (-/-)

Metrics	DsFlsmv	DsFhmedian	DsFkuwahara	DsFsrاد
PSNR	39.6 \pm 2.1 / 42.9 \pm 1.6	38.9 \pm 1.1 / 40.1 \pm 4.5	29.1 \pm 1.1 / 29.9 \pm 1.2	43.9 \pm 4.3 / 34.9 \pm 6.9
WSNR	34.8 \pm 1.8 / 38 \pm 0.91	33.1 \pm 1.1 / 35 \pm 5.4	18.8 \pm 0.9 / 20.6 \pm 1.3	39.1 \pm 5.2 / 25 \pm 8
VSNR	36 \pm 3.77 / 41 \pm 3.0	30 \pm 1.86 / 38 \pm 5.3	15 \pm 1.1 / 24.7 \pm 2.3	37 \pm 5.7 / 32 \pm 10
SSI	0.98 \pm 0.01 / 0.98 \pm 0.05	0.97 \pm 0.001 / 0.96 \pm 0.06	0.77 \pm 0.025 / 0.84 \pm 0.03	0.96 \pm 0.025 / 0.88 \pm 0.08
IFC	7.2 \pm 0.93 / 6.2 \pm 0.98	6.1 \pm 0.6 / 4.6 \pm 1.3	1.9 \pm 0.08 / 1.4 \pm 0.21	6.6 \pm 2.3 / 3.7 \pm 2.1
NQM	35.3 \pm 1.9 / 29 \pm 1.9	34 \pm 1.4 / 26.7 \pm 5.1	17.7 \pm 1.1 / 14.2 \pm 1.3	34.8 \pm 4.9 / 24.1 \pm 6.7

PSNR: Peak signal to noise ratio, WSNR: Weighted signal-to-noise ratio, VSNR: Visual signal-to-noise ratio, SSI: Structural similarity index, IFC: Information fidelity criterion, NQM: Noise quality measure

DISCUSSION

In this work we present an integrated software system for despeckling ultrasound videos. The integrated software system was evaluated by medical experts and also used in a number of other studies performed by our group (as also presented in Table 1) with very promising results. Our effort was to achieve multiplicative noise reduction in order to increase visual perception by the experts but also to make the videos suitable for further analysis such as video segmentation and coding.

The proposed system can also apply ultrasound video normalization, as documented in a few recent studies performed by our group (Loizou, 2012a; Loizou, 2012b; Loizou, 2012c), where ultrasound video normalization was carried out as also described in this study. It was shown in Loizou (2012b) that ultrasound

video normalization before despeckle filtering improved the video quality based on the visual evaluation by the experts. In (Loizou, 2012c), video despeckle filtering was applied prior to the segmentation of the intima media complex of the carotid artery from ultrasound videos, whereas normalization was also applied in (Loizou, 2010), for the generation of the M-mode image from ultrasound videos of the CCA.

While there are a number of commercial software packages proposed in the literature for denoising and/or analyzing ultrasound images (see also Table 1), we found no other studies in the literature for despeckle filtering in ultrasound videos of the CCA. A number of studies have investigated additive noise filtering in natural video sequences (Chan, 2005; Dabov, 2007; Maggioni, 2012; Rusanovsky, 2006; Zlokolica, 2002; Zlokolica, 2008). The usefulness of these methods in ultrasound video

Table 3. Percentage scoring of the original and despeckle videos by the experts (Loizou, 2012b)

Experts	original	DsFlsmv	DsFhmedian	DsFkuwahara	DsFsrاد
Average %	37	74	73	71	56

denoising on multiplicative noise still remains to be investigated. The DsFlsmv filter was found to perform better than other despeckle filters in two different studies presented by our group (Loizou, 2005; Loizou 2006). Loizou et al. (2007b) proposed a software system based in MATLAB® for the segmentation of the atherosclerotic carotid plaque, which was applied in 80 ultrasound images of the CCA. The system was evaluated based on visual perception by two medical experts and quantitative measures extracted from the images, where it was shown that the best despeckle filtering method was the DsFlsmv. An IMT MATLAB® based segmentation system was also proposed in (Loizou, 2007a), which was evaluated in 100 ultrasound images of the CCA. The DsFlsmv filter was used prior to the segmentation of the IMT (Loizou, 2007a; Loizou, 2009) and also prior to the segmentation of the atherosclerotic carotid plaque in ultrasound images (Loizou, 2007). The same system was later (Loizou, 2009) further developed in order to be able to segment the media and the intima layers of the CCA, where the DsFlsmv filter was used to despeckle the image prior to segmentation.

Limitations of the Video Despeckling Method

There are some limitations in the proposed methodology which are summarized below. MATLAB® is not the most computationally efficient environment. However, most of the implemented algorithms, programmed in MATLAB® are fast enough, in particular in segmenting and manually defining structures, as well as if the users can effectively define ROI and crop images to reduce the image dimensions using the available tools in the software. Therefore, computation speed is not a limiting factor for our software tool as the filtering can be applied in an ROI.

Another issue is that some automatic algorithms use many user-configurable parameters, such as the size of the moving window, the number of iterations and the coefficient of variation with the user trying to choose

the best parameter values. We have chosen in this application default values to be used as initial values for the parameters based on our experience. However, in many scenarios these parameters may still need to be changed by the user to achieve optimal results.

Validation of the final results is one of the most challenging tasks in medical image analysis applications. Results are usually compared with the “gold standard”, such as the optical perception evaluation by specialists, as also performed in this study. It is true that, such comparisons are often affected by other issues, such as, for example, inter- and intra-observer variability (Loizou, 2008; Loizou, 2007a; Loizou, 2007b; Loizou, 2012a; Loizou, 2009). However, it is relatively safe to view about such automated methods as “second readers” intended to aid the user as this has been shown in many Computed Aided Design (CAD) applications to be a useful approach.

An average processing time is about 3 seconds per frame (on an Intel Core i5-3470 processor with 3.2 GHz and 1GByte of RAM) for the video despeckling. It should be noted that the processing time of the proposed method could be further reduced by applying despeckle filtering only on key frames of the videos. Furthermore, software optimization methods (i.e. the MATLAB® software optimization toolbox) could be investigated for increasing the performance of the proposed video despeckling software system.

CONCLUSION

In this paper, a freeware despeckle filtering toolbox for ultrasound video has been presented that can be downloaded from (<http://www.cs.ucy.ac.cy/medinfo/>). The toolbox proposed in this study is based on the following four despeckle fitters, DsFlsmv, DsFhmedian, DsFkuwahara and DsFsradi. The toolbox also supports quantitative evaluation metrics between the original and the despeckled videos, as well as qualitative evaluation by the experts. Additional features of the toolbox include the computing of texture

features over selected ROIs on the original and despeckled videos. The system was evaluated on atherosclerotic carotid plaque ultrasound videos, where it was shown that the filters Ds-Flsmv, and DsFhmedian improved video quality perception (based on the expert's assessment and the quantitative video quality metrics). It is anticipated that the system could help the physician in the assessment of cardiovascular video analysis. However, exhaustive evaluation of the despeckle filtering toolbox has to be carried out by more experts on more videos.

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