

Segmentation of Atherosclerotic Carotid Plaque in Ultrasound Video

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Abstract— The degree of stenosis of the common carotid artery (CCA) but also the characteristics of the arterial wall including plaque size, composition and elasticity represent important predictors used in the assessment of the risk for future cardiovascular events. This paper proposes and evaluates an integrated system for the segmentation of atherosclerotic carotid plaque in ultrasound video of the CCA based on normalization, speckle reduction filtering (with the hybrid median filter) and parametric active contours. The algorithm is initialized in the first video frame of the cardiac cycle with human assistance and the moving atherosclerotic plaque borders are tracked and segmented in the subsequent frames. The algorithm is evaluated on 10 real CCA digitized videos from B-mode longitudinal ultrasound segments and is compared with the manual segmentations of an expert, for every 20 frames in a time span of 3-5 seconds, covering in general 2 cardiac cycles. The segmentation results are very satisfactory with a true negative fraction (TNF) of 79.3%, a true-positive fraction (TPF) of 78.12%, a false-positive fraction (FPF) of 6.7% and a false-negative fraction (FNF) of 19.6% between the ground truth and the presented plaque segmentations, a Williams index (KI) of 80.3%, an overlap index of 71.5%, a specificity of 0.88 ± 0.09 , a precision of 0.86 ± 0.10 and an effectiveness measure of 0.77 ± 0.09 . The results show that integrated system investigated in this study could be successfully used for the automated video segmentation of the carotid plaque.

I. INTRODUCTION

The size and composition of the carotid atherosclerotic plaque have been shown to be independent predictors of future cardiovascular events [1] with vulnerable plaques described as containing a large lipid core, a thin fibrous cap and dense macrophage inflammation in or beneath its surface whilst stable plaques are characterized by larger quantities of calcium and collagen and less lipids and inflammatory cells [2]. Accurate and precise segmentation of the atherosclerotic carotid plaque in ultrasound B-mode video allows for the extraction of different anatomical and biomechanical properties of the artery wall and plaque that can be most useful to the physicians for the evaluation of

plaque development and the process of atherosclerosis in modeling and evaluating the risks for future cardiovascular events. Ultrasound, elastography and other imaging methods such as spectroscopic photoacoustic imaging can be integrated to advance the characterization of the plaques and corresponding vulnerability [3] as the variation in the mechanical properties of the different tissue types is huge [4]. For example, the elasticity modulus of calcified plaque material is 50 times higher than the modulus of cellular plaque tissue [1]. Over the past few years different methods have been developed for the evaluation of different displacement and strain maps for sequences of longitudinal ultrasound scans of the carotid artery [5] as well as plaque heterogeneity and plaque echogenicity and their improvements are continuing [2]-[5]. The availability and evaluation of different characteristics of carotid plaque is of utmost importance especially since it is widely accepted that the experts are only moderately confident that there is adequate evidence to determine which interventions to use for different patient populations [3]. However the manual segmentation of the plaques in the carotid artery in ultrasound video, or over large sequences of images is not only a tedious and time consuming task, but also varies from large inter and intra observer variability and it is difficult to trace boundaries for each time frame of the cardiac cycle and for large volume of data sets [6], [7]. The need exists for the development of new tools and techniques for the assessment of the risk of stroke.

To the best of the authors knowledge there is only one published study for the segmentation of atherosclerotic carotid plaque in ultrasound CCA videos [7]. The method by Destremes et al. [7] is based on a Bayesian segmentation model and is evaluated on 33 video sequences. Still, several other studies investigate the segmentation of atherosclerotic carotid plaque in ultrasound images. Hamou et al. [8], proposed a method based on the Canny edge detector to detect the plaque in longitudinal carotid artery ultrasound images. A morphological based approach for the carotid contour extraction was proposed in [9]. Mao et al. [10], proposed a discrete dynamic contour model for extracting the carotid artery lumen in 2D transversal ultrasound images, whereas Abolmaesumi et al. [11] introduced a method based on the star algorithm for the plaque segmentation in transversal carotid ultrasound images. A semi-automatic method for plaque segmentation in 3D images of the carotid artery using the Balloon model introduced in [12] was proposed by Gill et al. [13]. Loizou et al. [6] proposed a plaque segmentation method for the extraction of the plaque in 80 ultrasound images of the CCA using an automated contour estimation. The plaque in [14] was segmented in 56 2D longitudinal images using a gradient based snake segmentation method and fuzzy K-means algorithm. In [15],

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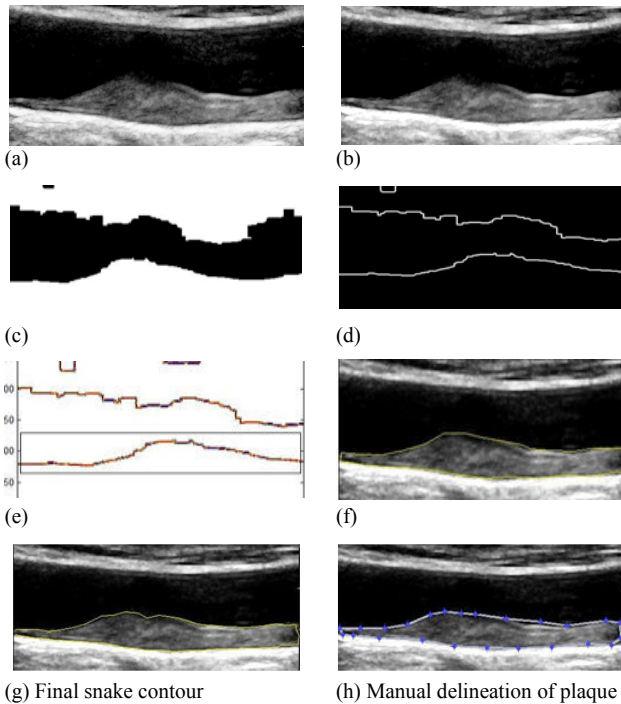


Fig. 1: Plaque contour initialization procedure and final snakes contour: (a) First frame of the original ultrasound video, (b) Normalised despeckled frame image with hybrid median filter (2 iterations, window 5x5), (c) binary image frame after dilation with a square window shape of size 9 after removing edges, (d) edge image frame after removal of undesired edges, (e) interpolating spline and detected initial contour with contour selection, (f) initial snake contour mapped on the first video frame, (g) final snake contour after snakes deformation, (h) manual delineation of plaque.

the Hough transform were applied to perform segmentation of plaque in 10 2D cross sectional ultrasound images of the carotid artery.

In this paper an integrated system for the segmentation of the atherosclerotic carotid plaque in 2D ultrasound video of the common carotid artery (CCA) is proposed and evaluated. The system builds on some of the authors' previous work [6], and incorporates normalization, speckle reduction filtering, and snakes segmentation for the advancement of evaluation and treatment of carotid atherosclerosis.

II. MATERIALS & METHODS

A. Recording of Ultrasound Videos

A total of 10 B-mode longitudinal ultrasound videos of the CCA bifurcation were recorded. The images were acquired by the ATL HDI-5000 ultrasound scanner (Advanced Technology Laboratories, Seattle, USA) [16] with a resolution of 576X768 pixels with 256 gray levels, a spatial gray resolution of 17 pixels per mm (i.e. the resolution is 60 μ m) and having a frame rate of 100 frames per second. All video frames were manually resolution-normalized at 16.66 pixels/mm (see Section II-C). 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 [17]. The images were recorded at the Saint Mary's Hospital, Imperial

College of Medicine, Science and Technology, UK, from symptomatic patients at risk of atherosclerosis and have already developed clinical symptoms, such as a stroke or a transient ischemic attack (TIA). The video segmentations were performed for 3-5 seconds intervals, covering in general 2-3 cardiac cycles.

B. Manual Plaque Segmentation and classification

An expert (vascular surgeon) manually delineated the plaque borders every 20 frames, between plaque and artery wall, and those borders between plaque and blood, on 10 longitudinal B-mode ultrasound videos of the carotid artery, after image normalization and speckle reduction filtering (see section II.C and section II.D), using MATLAB software developed in our group.

C. Video Normalization of Ultrasound Videos

Brightness adjustments of ultrasound videos were carried out in this study based on the method introduced in [18], which improves image compatibility by reducing the variability introduced by different gain settings, different operators, different equipment, and facilitates ultrasound tissue comparability. Further details of the proposed normalization method can be found in Algebraic (linear) scaling of the first video frame was manually performed by linearly adjusting the image so that the median gray level value of the blood was 0-5, and the median gray level of the adventitia (artery wall) was 180-190 [18]. The scale of the gray level of the images ranged from 0-255. Thus the brightness of all pixels in the image was readjusted according to the linear scale defined by selecting the two reference regions. The subsequent frames of the video were then normalized based on the selection of the first frame.

D. Speckle Reduction Filtering

In this study the filter DsFhybridmedian, which was introduced in [19] and which produces the average of the outputs generated by median filtering with three different windows (cross shape window, x-shape window and normal window) was applied to each consecutive frame prior to plaque segmentation. The DsFhybridmedian filter was applied twice to each video frame using a 5x5 pixel moving window.

E. Plaque Contour Initialization

A plaque initialization procedure was carried out for positioning the initial snake contour in the first frame of the video, as close as possible to the area of interest. The procedure is described as follows (see Fig. 1): 1) Load the first video frame, perform normalization (in the first frame) (see section II.C) and despeckle filtering (see Section II.D) and apply to all consecutive video frames. The normalized despeckled first video frame is shown in Fig. 1b). 2) Binarize the image in order to extract edges more easily (see Fig. 1c). 3) Dilate the binary image (from point 3) above) by applying a dilation morphological operation that grows the binary image area (see Fig. 1c). 4) Perform edge detection on the binary dilated image and extract the contour matrix of the image (see Fig. 1d). Select using the mouse the area of interest on the image, where the plaque will be detected and extract the contour matrix of the above area by locating points and their coordinates on the plaque borders (contour) and construct an interpolating B-spline (see Fig. 1e). Sample the interpolating B-spline in 30 equal segments, in order to

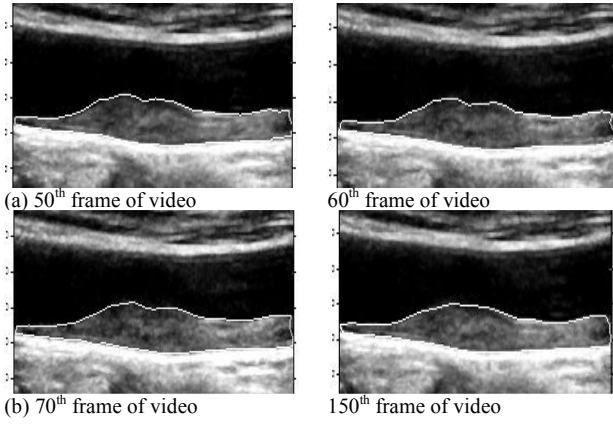


Fig. 2: An example of plaque segmentation with plaques appearing at the CCA at the 50th, 60th, 70th, and 150th video frame of the video.

define 30 snake elements on the contour. Connect the first and the last snake points on the initial contour to form a closed contour. 5) Map the detected contour points from 4), on the first frame of the video (see Fig. 1f) to form the initial snake contour for the plaque borders (see Fig. 1f). 6) Deform the initial contour by the snake to accurately locate the plaque-blood borders (see section II.F), and save the final plaque contour and display it on the B-mode image (see Fig. 1e). 7) Map the final snake contour from the first video frame, on the second frame of the video, deform by the snake to detect and save the final plaque borders.

F. Snakes Segmentation

The Williams & Shah snake segmentation method [20] was used to deform the snake and segment the plaque borders. The method was proposed and evaluated in [6], in 80 ultrasound images of the CCA and more details about the model can be found there. For the Williams & Shah snake, the strength, tension and stiffness parameters were equal to $\alpha_s = 0.6$, $\beta_s = 0.4$, and $\gamma_s = 2$ respectively. The above procedure was applied in cases where there was only one plaque present in the CCA video. In cases where multiple plaques were located (this fact holds for 22 out of 43 videos), thus forming multiple connected regions (see Fig. 2, left column), the proposed segmentation method was applied independently on each plaque component.

H. Evaluation of the Segmentation Method

ROC analysis [21], to assess the specificity and sensitivity (R) of the video segmentation method by the true-

positive fraction, TPF, and false-positive fraction, FPF, [21]. The TPF, is calculated when the expert detects a plaque pixel (when a plaque pixel is present) and the computerized method identifies it as so, whereas the FPF, is calculated when the expert detects no plaque pixel and the computerized method incorrectly detects that there is a plaque pixel present. The TNF fraction is calculated when the expert identifies no plaque pixel and the computerized method identifies it as so (absent), whereas the FNF is calculated when the expert identifies plaque pixel presence and the computerized method incorrectly identifies plaque pixel absence. Ratios of overlapping areas, can also be assessed by applying the similarity kappa index, KI, [22], and the overlap index [23]. These indices were computed as follows:

$$TPF = \frac{|AS \cap GT|}{|GT|}, \quad FPF = \frac{|AS| - |GT|}{|GT|}, \quad TNF = \frac{|AS \cap GT|}{|AS|}$$

$$FNF = \frac{|AS| - |GT|}{|AS|}, \quad KI = 2 \frac{|GT \cap AS|}{|GT| + |AS|}, \quad overlap = \frac{|GT \cap AS|}{|GT \cup AS|} \quad (1)$$

where $\|$ denotes the magnitude, \cap denotes the intersection (the number of common pixels in the manual and the snakes segmented areas), and \cup the union (the number of all pixels defined by the manual and the snakes segmented areas where the common pixels are considered only once). GT , denotes the number of pixels defined by the segmented area, representing ground truth delineated by the expert, \overline{GT} , its complement, and AS the number of pixels belonging in the area, obtained by the snakes segmentation method. The intersection gives the probability that both AS and GT occur and the union is the probability that either AS or GT occur. The specificity, $Sp = 1 - FPF$, the precision, P , and an effectiveness measure, $F = 2 * (P * R) / (P + R)$, [21] were also calculated to describe the ROC characteristics of the segmentation methods with .

III. RESULTS

Figure 2 presents an example of video plaque segmentation with plaques appearing at the CCA in the left and right column respectively, at the 50th, 60th, 70th, and 150th video frames of the videos. It is the case of a 64-year old male symptomatic subject, with a stenosis of 40-50% and a stent on the right CA.

Table I tabulates the results of the ROC analysis based on TNF, TPF, FNF, FPF, KI, overlap index, Sp , P , and F , for the

TABLE I
ROC ANALYSIS BASED ON TNF, TPF, FNF, FPF, KI, OVERLAP INDEX, Sp , P , AND F , FOR THE PROPOSED VIDEO SEGMENTATION METHOD ON 10 ULTRASOUND VIDEOS OF THE CAROTID ARTERY, USING MANUAL SEGMENTATIONS PERFORMED BY AN EXPERT

Segmentation Method	Ultrasound Data	System Detects	Expert Detects no plaque	Expert Detects plaque	KI	Overlap Index	Sp	P	F
Loizou [6] (N=80)	Images	No plaque Plaque	TNF=80.9% FPF=5.9%	FNF=15.6% TPF=82.7%	80.7 %	69.3 %	0.94	0.93	0.86
Golemati [15] (N=14)	Images	No plaque Plaque	-	- TPF=97.5±1.0%	-	-	0.96±0.01	-	-
Destremes [7] (N=33)	Videos	No plaque Plaque	-	TPF=83.7±8.3% -	-	-	0.94±0.04	0.85±0.75	0.75±0.1
Present study (N=10)	Videos	No plaque Plaque	TNF=79.3% FPF=6.7%	FNF=19.6% TPF=78.12%	80.3%	71.5%	0.88±0.09	0.86±0.10	0.77±0.09

proposed video segmentation method performed for one cardiac cycle, on 10 ultrasound videos of the CCA. The results of the automated segmentation method are compared with the manual tracings of the expert which are considered the Ground Truth. The results show that the presented method (see last row of Table I) agrees with the expert by correctly detecting no plaque (TNF) in 79.3% of the cases, by correctly detecting a plaque (TPF) in 78.12% of the cases, disagrees with the expert by detecting no plaque (FNF) in 19.6% of the cases, and by detecting a plaque (FPF) in 6.7% of the cases. The similarity kappa index KI, and the overlap index, for the proposed video snakes segmentation method were, equal to 80.3% and 71.5% respectively. The specificity, Sp, precision, P, and F were 0.88 ± 0.09 , 0.86 ± 0.10 and 0.77 ± 0.09 respectively.

IV. DISCUSSION

The results of the proposed semi automatic video segmentation method can be favorably compared to the results of the segmentation of the carotid plaque in ultrasound images presented in our recent study [6], and also with the results presented in [7] and [15] (see Table I). Comparing the proposed video segmentation technique with our previous study in [6], one can see that the TPF, KI and overlap index are smaller. This may be attributed to the much larger amount of data that the method is evaluated on as well as the quality of the videos compared to the images.

The average computation of the snake contour was about 15 seconds per frame. Taking into account that the expert clinician required over 25 seconds per frame for the manual delineation and the fact that there are about 500 frames per cardiac cycle, there is an average time saving of 8 minutes per video assuming manual segmentation is carried out every 20 frames. It should also be noted that the accuracy of the method may be improved if the first frame snake initialization is more accurate. In [14] and [15] images were neither normalized nor despeckled nor an automatic contour estimation was used as in this study. The normalization used ensures that the method and the results are not dependent on the equipment used. This is not the case for the video segmentation method proposed in [7], where the region based segmentation was established using the statistical distribution of the gray level of the frames whilst speckle noise was not taken into consideration.

Further improvement could be achieved to enable the use of the proposed video segmentation technique in the real clinical praxis if the initialization of the snake contours (see Section II.E) is applied every 30 or 40 frames so that the snake contour is repositioned closer to the plaque borders.

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