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User-independent Plaque Characterization and Accurate IMT Measurement of Carotid Artery Wall using Ultrasound

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Abstract—**Non-invasive plaque characterization of the carotid wall is crucial for the early assessment of pathology, as well as for the monitoring of the progression of a degenerative phenomenon. Specifically, in clinical practice the carotid wall status is assessed by means of B-Mode ultrasound scans. We recently implemented an algorithm for the segmentation of the common tract of the carotid wall using ultrasound relative to healthy subjects [5].**

This paper presents a superior strategy for plaque characterization, which accurately determines both echolucent-type II and echogenic plaques in pathologic subjects. We preserve both user-independence and pixel fuzziness in our approach, thereby designing an accurate intima-media thickness (IMT).

Our database consists of 20 subjects comprising of normal, stable (echogenic) and unstable (echolucent) plaques. In this database of 45 images, we demonstrate our performance with respect to the gold standard tracings to an accuracy determined as normalized error to be about 8%. The results are very promising and this algorithm is being integrated into clinical setup for automatic pathologic carotid wall analysis.

I. Introduction

Cardiovascular diseases (CVD) are responsible for one third of all the global mortality due to pathology. The World Health Organization revealed that by 2010 cerebrovascular and cardiac diseases would be responsible for 20% and 26% of the global deaths respectively. Nowadays, CVDs are a specific problem of industrialized countries, but, by 2040, it is believed that CVDs will affect also emerging and third world countries. Early prevention is the key point to successfully lower the impact of the CVDs on health.

Several studies evidenced the relationships between the carotid artery wall status and CVDs [1]; specifically, an increased intima – media thickness (IMT) is correlated to an augmented risk of brain infarction or cardiac attack. Moreover, the presence of a carotid plaque has been correlated not only to CVDs, but also to degenerative pathologies like vascular dementia and Alzheimer's disease [2]. Hence, the assessment of the carotid wall status is essential for the early identification of risk conditions also in asymptomatic patients.

A suitable clinical examination for the early detection of carotid wall pathologies has to be non – invasive, low – cost, fast, highly repeatable, user independent, and safe for the subjects. Ultrasound scanning is a technique that possesses all the above-mentioned characteristics; in clinical practice, the carotid artery status is usually assessed by means of B-Mode longitudinal images.

A major problem of this clinical examination is the need for quantitative measures [3]: besides IMT, or the degree of stenosis, in presence of a plaque an accurate analysis of the carotid wall/plaque texture has to be carried out [4]. A trained operator usually performs segmentations and measurements directly on the device console. This manual operation has the following drawbacks: i) it is not operator – independent, ii) it decreases the repeatability of the exam, and iii) it is not suitable for large image databases of already acquired pictures. Moreover, when segmenting a ultrasound image containing a plaque, inter-operators variability greatly increases.

Recently we proposed a completely user – independent algorithm for the segmentation of the carotid wall B-Mode images (CULEX) [5] and we characterized its performances on a large database of images obtained on healthy subjects [6]. Unlike previously developed algorithms [7], our approach does not require any user interaction; hence it ensures the highest repeatability of the results. Moreover, we showed that our algorithm is useful not only to calculate IMT, but also to derive the profiles of the intima and media layers of the carotid wall on a large tract of the image, allowing a more focused analysis of the carotid wall itself.

In this paper, we propose a modified version of the CULEX algorithm, which can be applied to images containing plaques. This second version (CULEX2) enables the user to automatically derive the lumen – intima (LI) and the media – adventitia (MA) interfaces of a wide tract of the common carotid artery on any kind of ultrasound B-Mode image. Hence, it can be used for segmentation or as a starting point for the computer – aided diagnosis of carotid plaques. To our knowledge, our methodology is the only one

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that provides a reliable segmentation of plaques, without any initial contour or seed decided by the user.

The paper is organized as follows: section II describes the algorithm and the image database we used to characterize its performance, section III presents the results and provides segmentation examples, section IV reports the system performance, section V focuses on the discussion of the clinical applications of the algorithm and section VI presents our conclusions.

II. MATERIALS AND METHODS

A. Description of the algorithm

The first version of our algorithm consisted of three stages: a) ROI identification; b) gradient – based segmentation; c) contour refinement by means of deformable parametric models. The first stage of the algorithm is the identification of the portion of the image where the CCA tunicae are located. To correctly identify this region, morphological considerations are crucial: the vessel lumen is characterized by pixels with low-intensity and relatively low variance, surrounded by high-intensity pixels belonging to the carotid walls. Hence, the basic idea is to search for high-intensity pixels possibly belonging to the distal adventitial wall, starting from the deepest imaged layers of the scan. A pixel is considered belonging to the adventitia tunica if its intensity is a local maximum and if at least a pixel belonging to the lumen is located above it. For each pixel in the image we derive two measures: the mean intensity and variance of a *10x10* square neighborhood. It may be shown that the bi-dimensional distribution of these two variables for the pixels belonging to the lumen is condensed in the lowest classes. An example of the distribution of neighborhood mean and variance for an image of a normal carotid is presented in Fig.1, where the black pixels represent lumen pixels, while the gray pixels are all the other pixels in the image. Similar results are reported in [5]. Once the ROI is identified, a gradient-based technique provides a first initial segmentation, which is then refined by applying an active contour. A detailed description of this first version of the algorithm is provided in [6]. Fig. 2 reports the CULEX segmentation of a normal carotid: the continuous lines represent the LI and MA interfaces, whereas the dash-dotted lines represent the ROI identification.

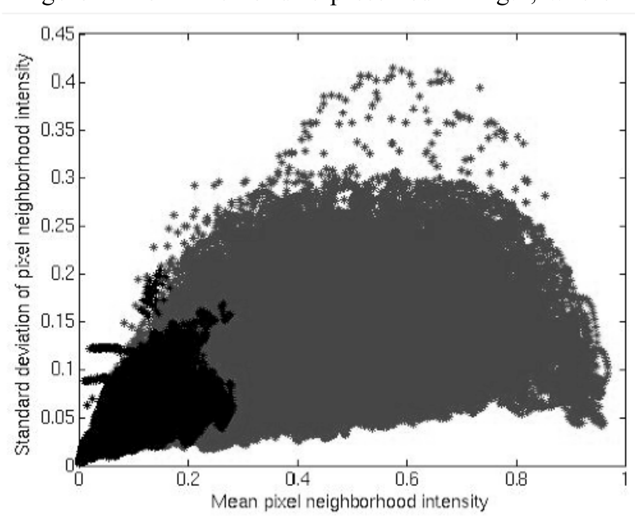

Fig. 1. Average value and standard deviation of the pixel neighborhood intensity (normalized values). The pixels belonging to the carotid lumen are depicted in black, while the gray pixels represent the total number of pixels in the image. It is evident how the pixels belonging to the lumen are located in the first classes.

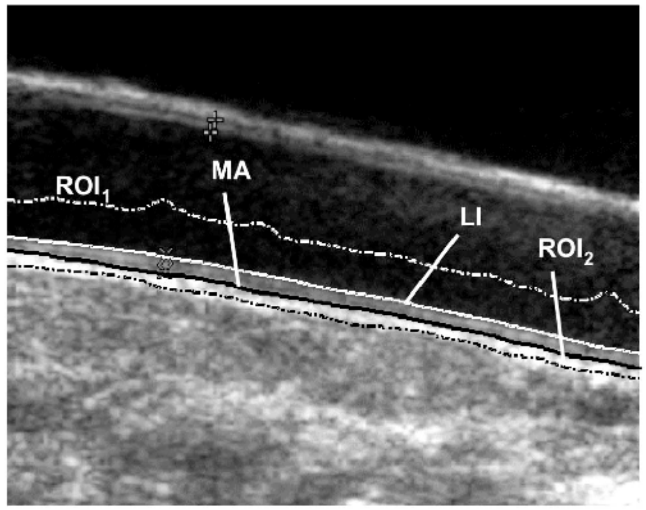

Fig. 2. CULEX Segmentation. The black and white dash-dot lines represent the limits of the automatically identified ROI. The black and white continuous lines represent the LI and MA interfaces respectively.

When in presence of carotid wall pathology (increased IMT or plaque) the bidimensional diagram of the neighborhood mean and variance may be altered. Also, the gradient-based segmentation is expected to give poor results when applied to echolucent plaques, whose gray tones are very close to the gray of the lumen pixels. Hence, to correctly segment the carotid wall, we introduced a fourth step to the original algorithm. After having derived the LI and MA interfaces, we recomputed the bidimensional distribution of neighborhood mean and variance for the pixel comprised between the ROI_1 and MA profiles. This step focuses the analysis of the media layer, which is responsible for the pathologies of thickening and plaque formation.

A simple fuzzy K-means algorithm was employed. The purpose of the algorithm was the extraction of the arterial wall also in presence of heterogenous/lipidic plaques, so three different classes were employed: a first class, designating the arterial lumen, a second class, corresponding to the normal arterial intima-media layer and a third class, who conceptually corresponded to the echographically heterogenous tissue characteristic of echolucent plaques. Two input features were used, i.e. the intensity and variance of the 3x3 neighborhood of each pixel. Class tags were automatically assigned on the basis of the mean intensity values of pixels belonging to the different classes, with the lowest mean value corresponding to the lumen class and the highest to the normal adventitial wall. The mean intensity

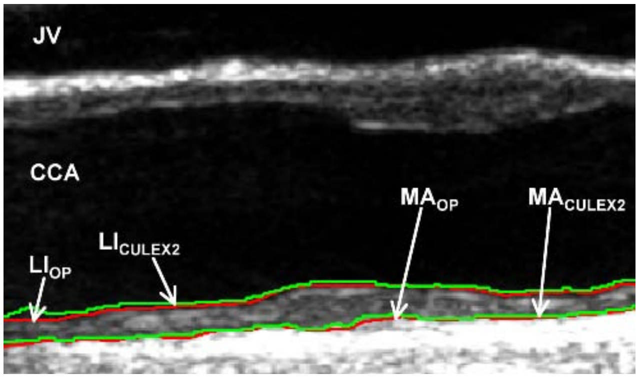

Fig. 3. Segmentation of a homogeneous echogenic plaque. The computer generated MA interface (MA_{CULEX2}) is overlapped to the operators contour (MA_{OP}), whereas the LI_{CULEX2} profile little overestimates the plaque. Red lines are relative to operator segmentations; green lines are relative to computer-generated segmentations (color figure).

value for each class was obtained by the weighted mean of the intensity values, with the weight given by the degree of membership to the class.

The use of a fuzzy classification allows additional degrees of freedom in the choice of the thresholds for the successive defuzzification. This choice was crucial for the designation of the third class: values of the threshold around 0.5 were found to be more accurate for the segmentation of the normal wall, whereas values around 0.3 were found to be more appropriate in presence of pathology. Pixels belonging to the second and third class were finally classified as belonging to the wall, whereas pixels belonging to the first class were designated as lumen.

The CULEX2 algorithm, together with a graphical user interface, was developed and implemented in MATLAB (The MathWorks, Natick, MA, USA).

B. Image database

We selected 45 images derived from a population of 20 patients (age range 41-89 years). Fifteen images were relative to intima – media thickening (IMT values ranging from 0.09 cm to 0.59 cm), 15 to homogeneous echogenic (stable) carotid plaques, and 15 to inhomogeneous echolucent-type II (unstable) plaques. All the images were relative to the common tract of the carotid artery, insonated according to international recognized standards [1].

Subjects were randomly selected among the patients who performed ultrasound examinations in the Neurology division of the Presidio Sanitario Gradenigo of Torino. All of them signed an informed consent before being enrolled in this study.

C. Acquisition device

A Philips ATL HDI 5000 ultrasound scanner was used for the acquisitions. B-Mode images were obtained by means of a 50 mm linear probe (model L12-5). All the images were transmitted by the device to a computer in DICOM3 format, discretized on 8 bits, and represented by means of a grayscale linear mapping of the pixel intensity.

III. RESULTS

A. Detection of carotid echogenic plaques

Fig. 3 reports the CULEX2 segmentation of an echogenic plaque on the CCA distal wall. It can be noticed how the LI and MA profiles are adherent to plaque morphology. The dash-dotted lines represent the average segmentation traced by the two experts that we used as ground-truth to compute the segmentation errors. Specifically, it can be observed that the MA profiles are almost overlapped, whereas CULEX2 tend to little overestimate the intima profile.

B. Detection of carotid echolucent plaques

Echolucent plaques are a major challenge for automatic segmentation. In fact, they are characterized by an extremely low echogenicity. A common method for detecting this kind of plaques is using Color Doppler: the presence of a plaque determines a black zone corresponding to the absence of blood flow. However, when in duplex modality (i.e. when the representing both the B-Mode and the Doppler information) the spatial resolution and the temporal resolution of the device decrease. This may produce a poor estimation of the plaque dimensions and modifications of plaque texture.

Our algorithm proved effective in segmenting inhomogeneous echolucent plaques. Fig. 4 depicts a distal CCA wall echolucent plaque and the segmentation obtained by CULEX2. Despite the algorithm performed a stricter segmentation with respect to human operators, the performances of the algorithm remain suitable for the user-independent detection of wall pathologies. On this image, the maximum error between the operator and the CULEX2 segmentation was of about 18 pixels for the LI interface and only of 5 pixels for the MA interface. The image in figure 4 represents the worst case among all the images in our sample database.

C. Increased IMT detection

For all the 15 images on which we tested the algorithm, we obtained segmentation performances comparable to those obtained on CCA images of healthy subjects. Figure 5 sketches the segmentation of a carotid wall with intima-media thickness equal to 0.11 cm (measured by an operator on the ultrasound device console). The segmentation is correct and in good agreement to the average contours traced by the two experts.

IV. PERFORMANCE EVALUATION

We evaluated the performance of the algorithm by comparing the automatic IMT segmentation to the average segmentation traced by the two experts. The segmentation error was defined as the absolute value of the ratio between the incorrectly classified pixels and the total number of pixels representing the wall [3].

For increased IMT images, the average error was equal to 12% of the total wall area, for echogenic plaques to 5% of the total wall area, and for echolucent plaques to 7% of the

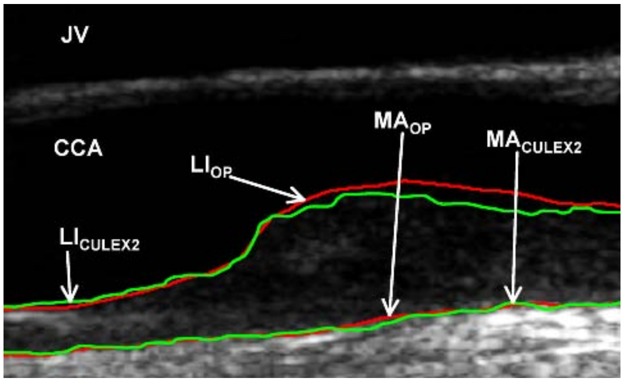

Fig. 4. Segmentation of a inhomogeneous echolucent plaque. Segmentation error was equal to 12.4% and this image represents the worst-case condition in our database. Red lines are relative to operator segmentations; green lines are relative to computer-generated segmentations (color figure).

total wall area. The overall accuracy on the 45-image database determined as normalized error was equal to 8%. Fig. 4 represents the worst-case in our database set: an echolucent-type II plaque in which segmentation error was equal to 12.4%.

Segmentation error is mainly due to the LI interface: the segmentation error we obtained segmenting the MA interface of pathologic images was not statistically different to that of normal carotid walls (data available in [6]). This error depends on the threshold used for defuzzification: we are developing an automatic threshold detection based on image characteristics.

V. Discussion

The CULEX2 algorithm is able to characterize both echogenic and echolucent plaques in the carotid wall and it is completely automatic. Pixel fuzziness and user-independence are preserved and obtained IMT design was extremely close to the gold-standard tracing.

On stable plaques and on increased IMT images the CULEX2 algorithm performed a segmentation substantially equal to that obtained on normal images. When processing echolucent plaques the segmentation error slightly increased because of the weak difference in gray tones between pixels belonging to the wall and pixels belonging to the lumen.

This second version of the algorithm is a step forward in the completely automatic detection of the LI and MA interfaces in a ultrasound B-Mode carotid scan, suitable for healthy as well as pathologic subjects.

VI. Conclusions and Future

This paper shows a completely user – independent algorithm for the segmentation of the lumen-intima and media-adventitia layers of carotid B-Mode images, that can be used also in presence of pathology. The algorithm proved effective in automatically detect and segment echolucent-type II plaques, echogenic plaques and carotid walls with increased IMT. Despite a small bias in the plaque dimensions estimation, we found the performance of our

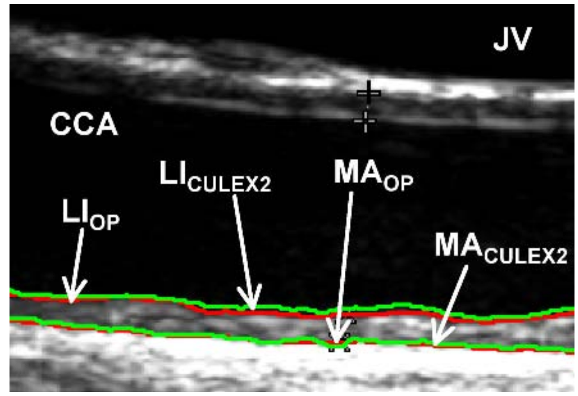

Fig. 5. Segmentation of a carotid wall affected by intima-media thickening (about 0.11 cm). The CULEX2 algorithm performs a correct layers extraction of the LI and MA interfaces. Red lines are relative to operator segmentations; green lines are relative to computer-generated segmentations (color figure).

algorithm extremely useful for the assessment of the carotid media layer, as a computer aid to the early diagnosis of wall degeneration in asymptomatic patients.

This system may be extremely helpful when segmentation is just as a preliminary step for further processing such as coregistration with other imaging techniques, 3D reconstruction, and carotid wall assessment. As an example, this automatic algorithm could be used for plaque identification before performing plaque texture analysis, especially when the effects of several image-processing steps need to be validated [8].

The results are very promising and the system is being integrated into clinical setup for automatic pathologic carotid wall analysis.

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