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Real-time measurement system for the evaluation of the Intima Media Thickness with a new edge detector

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Abstract—**The evaluation of the Intima Media Thickness (IMT) of the Common Carotid Artery (CCA) with B-mode ultrasonography represents an important index of cardiovascular risk. The IMT is defined as the distance between the leading edge of the lumen-intima interface and the leading edge of the media-adventitia interface. In order to evaluate the IMT, it is necessary to locate such edges. In this paper we developed an automatic real-time system to evaluate the IMT based on the First Order Absolute Moment (FOAM), which is used as an edge detector, and on a pattern recognition approach. The IMT measurements were compared with manual measurements. We used regression analysis and Bland-Altman analysis to compare the results.**

I. Introduction

THE measurement of the IMT of the carotid artery walls with B-mode ultrasound imaging is a very interesting technique because it is non invasive, extremely safe, well tolerated by patients, relatively inexpensive and it allows real-time visualization. For this reason, the IMT measurement has emerged as one of the most attractive techniques for the evaluation of both the anatomical extension and progress of atherosclerosis and for the reduction of cardiovascular risk in recent years.

In-vitro and in-vivo studies have shown that measures of the IMT correspond clearly with the pathological measures and the technique has a good reproducibility. Population studies conducted on men and women with different risk factors for atherosclerosis, have shown that a strong correlation exists between the measure of the IMT and the classical risk factors. A variation on the IMT measure has also been associated with diabetes mellito, hypercholesterolemia and hypertension. Hence, the analysis of the Ultrasound (US) images of the carotid may be considered key when predicting coronary diseases in subjects that have few risk factors or none at all.

IMT is defined as the distance between the leading edge of the lumen-intima interface and the leading edge of the media-adventitia interface. To locate such edges, a manual approach is usually used. However, such a method is time consuming and rather unreliable. Therefore, tracing results may depend on the experience, training and subjective judgment of the operator, thus involving a great inter- and intra-operator variability. This is very important since an increase in the variability of a single measurement necessitates increasing the number of subjects required in order to obtain a significant statistical power for the studies. Moreover, such an approach can not be applied to large databases of images.

Many efforts have been made in developing new automatic procedures to make this technique less operator dependent [1-4]. In this paper, an automatic technique for the IMT measurement, based on a new edge detector (i.e. FOAM) and a pattern recognition approach, is described.

II. Materials and Methods

To validate the system, in-vivo images were used. 42 short sequences from 15 patients (9 male) were analyzed, both with manual measurements and with the presented method (i.e. CARONTE, CARotid ON-line Thickness Estimator).

Both healthy and pathological patients took part in the study. Consequently, a wide range of carotid arteries were analyzed in order to test the behavior of the algorithm with different images.

US images were carried out by a skilled operator.

For validation purposes, we developed a Matlab version of CARONTE and a simple software to manually trace the contours (calipers of the US equipment are unreliable for this purpose and do not allow the tracing of splines).

The IMT value was assessed as the mean of the IMT values of every frame of the sequence. Accuracy was quantitatively validated by using the regression analysis and by Bland-Altman statistics.

Figure 1 shows a typical B-Mode US image of the carotid artery and a schematic illustration of the edges/interfaces in the echo signal. Meaning edges can be mapped on the following interfaces: near wall media-adventitia, far wall lumen-intima and far wall media-adventitia.

In US images, blood (vessel lumen) and wall layers show different properties in reflecting US waves because of their differences in density and elasticity. Vessel lumen and tunica media don't reflect US waves, thus allowing a good identification of the lumen-intima and media-adventitia interfaces.

The longitudinal section of the carotid appears parallel to the horizontal axis in our coordinate system. The probe is

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placed on the external surface of the neck of the patient, thus the orientation depends only on the position of the artery relating to the longitudinal axis of the neck. As the common carotid can be considered parallel to this axis, one

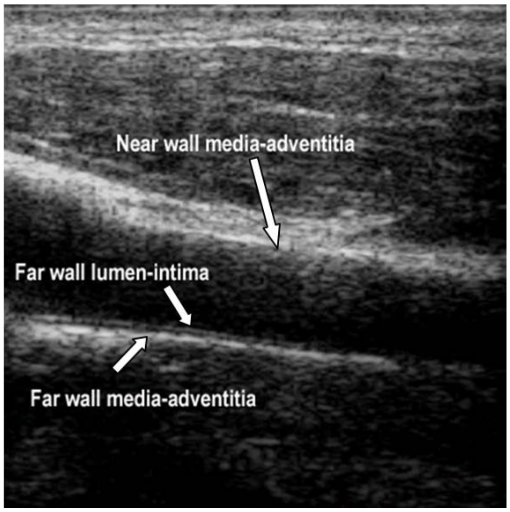

Fig. 1. Typical ultrasound B-Mode carotid artery image with the relevant edge/interfaces.

can then search for edges inside the Region-Of-Interest (ROI) by proceeding along the vertical axis. The IMT measure of the far wall is defined as the distance between the lumen-intima interface and the media-adventitia interface. Thus, the value of the IMT can be evaluated when the position of the interfaces is known. However, the presence of artifacts in the images due to speckle, reverberations and acoustic shadowing makes the precise location of these interfaces very difficult.

III. Real-Time Automatic Measurement System

The presented system has been implemented on a real-time embedded board.

A more detailed description of the hardware and software architecture of the board can be found in [5].

For the edge detection stage we used the FOAM as it has shown good performance regarding SNR when applied on US images compared to other traditional edge detectors such as Laplacian of Gaussian and Gradient of Gaussian [6].

A more exhaustive description of the mathematical operator and its use in general tasks of edge detection can be found in [7].

The system is fully automatic; the selection of a ROI is required only to limit edge detection operations in the area where the borders of the vessel are present.

The real-time feature of the system is highly recommended by physicians who, in this way, can have immediate feedback on the evaluated lumen-intima and media-adventitia interfaces.

A brief description of the system follows.

The video output signal of the US equipment is captured by the embedded board and shown by a Graphical User Interface (GUI) on a VGA monitor. Physicians have only to calibrate the system, trace the processing ROI and press the "Measure" button. Calibration is needed because the conversion factor pixel/mm varies with US equipment. ROI selection is useful to limit the area of the image where the edge detector is applied, thus reducing the computational load.

Subsequently, physicians only have to check the quality of the images and correct the probe position if the lumen-intima and media-adventitia interfaces disappear during the examination.

For every frame, the image processing scheme can be divided into four steps, described as follows:

- edge detection: ROI is filtered with the FOAM operator;
- search of the maximum values of the filtered output;
- removal of outliers with an iterative algorithm;
- evaluation of the IMT in the current image.

A. Edge Detection

Figure 2-a shows a common profile of the gray level intensities of a typical ROI (i.e. a column of the ROI) and figure 2-b the output of the FOAM operator on the same profile. This is due to the fact that points, which are internal to the vessel, are anechoic while tunica intima and tunica adventitia are the most reflective layers. Consequently, FOAM has a very low response to points inside the lumen.

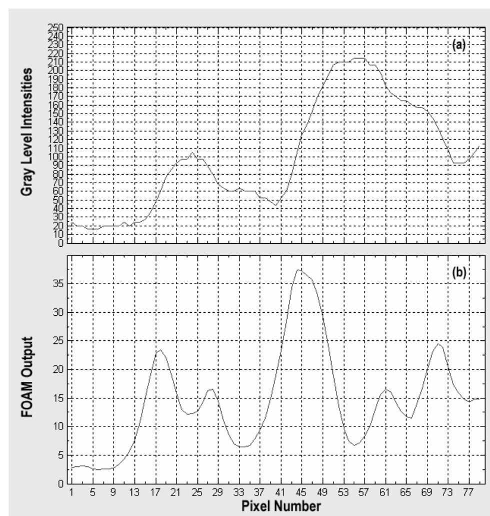

Fig. 2. A common profile of the gray level intensities of a typical column of the ROI and the output of the FOAM operator on the same profile.

The filter response of these points is near to zero. Starting from these points and moving toward the wall, the lumen-intima interface corresponds to the first relative maximum and the media-adventitia interface corresponds to the third one.

In figure 2-b a second relative maximum is also present; this maximum corresponds to the intima-media interface and it is present because of the great sensitivity of the FOAM operator. However, lumen and interface layers are not always clear and noiseless in real clinical images. Blood turbulences within the vessel can appear as gray points which are very similar to the edges highlighted by FOAM. Consequently, the reliability of locating accurately the intima-media interface is reduced.

We will show that a heuristic search for maxima with thresholds can overcome this problem.

So, we have to find the points of interest among local maxima.

B. *Heuristic Search*

A heuristic search is applied to every column of the ROI distinctly. The search algorithm can be divided into four steps:

- all local maxima are found and highlighted with a flag;
- the first maximum greater or equal to the absolute maximum of the FOAM in the column multiplied by a first threshold (TH_1) is searched for;
- the second maximum, following the first, greater or equal to the first maximum multiplied by a second threshold (TH_2) is searched for. The second maximum often corresponds to the absolute maximum;
- if both maxima are found, the column is flagged as "good", otherwise as "bad".

The local maxima found below the adventitia interface are not significant because their magnitude is always comparable with the maximum we found on the interfaces and, consequently, they are discarded.

The search algorithm is based on the following considerations:

- the lumen-intima and media-adventitia interfaces usually show a great response to the FOAM operator;
- the FOAM response is weaker than the response on the searched for interfaces due to blood turbulences and speckle noise artifacts;
- the intima-media interface shows a weaker response to FOAM than the lumen-intima and media-adventitia interfaces and we are able to discard these points with the presented approach.

As a result, we have columns labeled as "good" at the end of this stage. We can now analyze all the found points and, at the same time, refine the results.

C. *Outliers Removal*

This step is necessary to integrate all the information previously stored and to exploit the continuity of the searched for interfaces (i.e. the points that belong to the same interface should be connected). Consequently, isolated points are treated as outliers.

Moreover, the searched for interfaces, due to the small part of the vessel under examination, can be approximated as segments.

So, on every interface, we can proceed as follows:

- the least-square regression line that best fits the points is found;
- points that are farther from the line than a threshold (TH_PX_1), are discarded;
- a new least-square regression line that best fits the points that have not been discarded is found;
- the procedure is iterated until the last outlier is removed.

At the end of this stage, two regression lines are available, one for every interface.

D. *IMT Evaluation*

Now, three more controls are necessary before the IMT evaluation can be carried out. If one of these controls fails, the frame will be discarded.

First, after the outlier removal phase, every interface must be composed of a minimum number of points (TH_PX_2).

Second, the slopes of the two regression lines cannot differ more than a given angle (TH_ANG_1).

Third, the slope of each of the two regression lines cannot differ more than a given value (TH_ANG_2) from the mean value of the slope evauated in the five preceding frames.

If the frame has not been discarded, the IMT is evaluated as the distance between the mean point of the first regression line (intima-media interface) and the second regression line (media-adventitia interface).

TABLE I
ALGORITHM PARAMETERS

Name	Value
TH_1	0.4
TH_2	0.9
TH_PX_1	3 pixels
TH_PX_2	5 points
TH_ANG_1	5°
TH_ANG_2	3°

IV. Statistical Analysis

A total of 42 in-vivo sequences (3000 frames) with different image qualities were analyzed. The algorithm parameters are summarized in table 1.

A single value of IMT was evaluated on every sequence

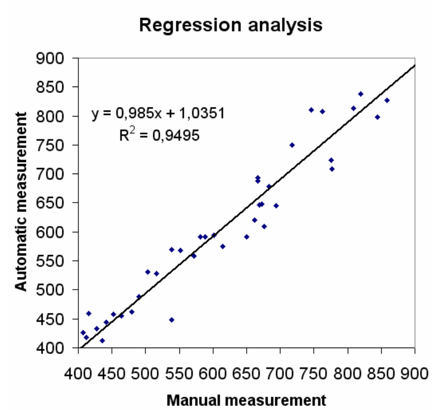

Fig. 3. Regression analysis of the 42 in-vivo sequences.

as the mean of the IMT values estimated on every frame.

The manual analysis was carried out by extracting 1/10 of the available frames from every sequence, the frames being equally spaced in time.

The automatic analysis was applied to all frames of the sequences, except to the frames rejected by the algorithm.

Regression analysis and Bland-Altman plots were used to compare the results.

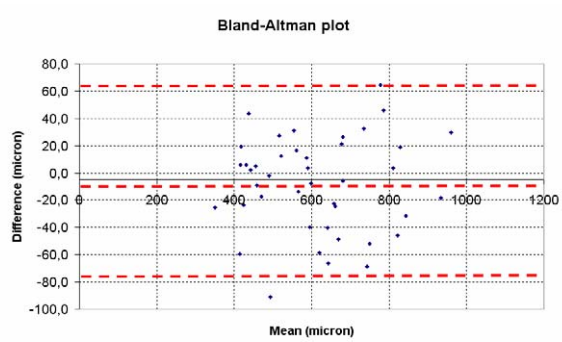

Fig. 4. Bland-Altman plot of the 42 in-vivo sequences.

The regression analysis is shown in figure 3. The slope was 0.98 with a 95% CI from 0.91 to 1.05 and the intercept was 1.03 with a 95% CI from -45 to 47. Figure 4 shows the difference between automatic and manual measures versus their means. The bias is -8.23 micron with a 95% CI from -19.19 to 2.72 micron and it is not significantly different from zero. The interval of agreement of the automatic method versus manual method is ±70 micron.

V. Results and Conclusions

A new system for real-time evaluation of the IMT at the carotid artery level has been presented.

The system is based on the edge detection operator called FOAM that is particularly suited for the analysis of US images and for fast real-time implementation.

The system is also based on a heuristic search and an outliers-removal phase that provide a very robust estimation of the interfaces which is, in turn, needed to asses the IMT value.

A set of ad-hoc parameters (table 1) are used during the above mentioned phases. However, TH_1, TH_2 and TH_PX_1 can affect only the number of the points which describe the interfaces being their position independent of such parameters. TH_PX_1, TH_ANG_1 and TH_ANG_2 can only discard or include the current frame in the computation of the overall IMT of the sequence. The value of the parameters was carried out with an experimental procedure. A skilled operator supervised the position of the interfaces founded by the algorithm and modified the parameters according to the results. 3000 carotid US images were used to evaluate the "optimal" value of the parameters. In this way, a set of parameters that best perform with a large variety of US images were obtained.

The statistical analysis showed encouraging results.

However, a more reliable validation should be achieved by comparing our method with a manual gold standard carried out from measures coming from several skilled operators since manual measures obtained from a single operator may be affected by a large variability.

In a future work, we plan to compare our method with a more robust manual gold-standard and with other similar automatic systems.

Moreover, our system presents another important feature: it can be used in a real-time environment thus allowing measurements to be carried out when the examination is still in progress. This is a great advantage because the operator can have immediate feedback on the quality of the images.

As regard the real-time execution timing, the power of the DSP used is high enough to guarantee a real-time execution of the algorithm at a frame rate of 25 frames/second. The timing of the main parts of the algorithms when the size of the ROI is 50 x 100 pixels are summarized as follows: edge detection (8.8 msec), heuristic search (0.7 msec), outliers removal (0.72 msec), IMT evaluation (0.12 msec), overall processing time for one frame including overhead due to GUI and mouse management and images acquisition (14.34 msec). Considering that the time available to process one image is 40 msec (European video standard), the results show how the CPU load is about 36%.

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