Fusion of Edge Enhancing Algorithms for Atherosclerotic Carotid Wall Contour Detection in Computed Tomography Angiography

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Abstract

The aim of this study is to assess the feasibility and performances of the fusion of edge enhancers in in vivo computed tomography angiography (CTA) images for automatic segmentation of outer and inner vessel walls, in presence of atherosclerotic plaques.

From 4 patients' CTA exams (stenosis degrees 70% – 95%) the slices representing plaques were extracted (223 images) and hand segmented by a trained operator for the vessel walls. The analyzed slices depict the common and internal carotid arteries and the carotid bifurcation.

The automatic protocol exploits two different categories of image edge enhancers: 5 edge detectors (Sobel, Prewitt, Roberts, laplacian of gaussian (LOG) and Canny) and 5 filters/mapping functions (laplacian filter, gradient map (GM), Otsu thresholding (OT), local range map (LRM) and standard deviation (STD) map).

The mean correlation coefficient between the manual and the automatic masks is 48% [17%, 64%]. By selecting the GM, LRM and STD algorithms only, the mean performance is improved up to 58%.

This methodology was proven to be comparable to the manual one. The correct selection of the edge enhancers is critical for the performance optimization: GM, LRM and STD showed to be the most suitable for our purpose.

1. Introduction

Atherosclerosis is a systemic disease, defined by the American Heart Association as the accumulation of atherosclerotic plaque inside arteries. The atherosclerotic plaque develops with the buildup of cholesterol (low-density lipoproteins - LDL - as a precursor to the disease), fatty substances, various metabolites from surrounding cells, calcified and fibrotic tissues [1–3]. Diagnostic and characterization of the disease in arteries, more specifically in the carotid arteries, may lead to the prevention of future strokes [4,5]. The atherosclerotic plaque is usually located in or around the carotid bifurcation since this location presents the highest variance of wall-shear stress and artery wall stiffness. The former is one of the precursors of the development of the disease [6], the latter is associated with plaque composition [7] and both linked with plaque stability. To be able to study the impact and presence of arterial stiffness there is the need to separate in the CTA image the outer vessel from the surrounding tissues and the inner border from the lumen.

There are algorithms that allow to segment the carotid artery wall but the need for human intervention prevails for the initialization, parameterization or validation of results [8]. Manual segmentation is done by trained operators, by using two regions of interest (ROI) representing the carotid outer contour and the lumen contour, with the carotid wall defined as the difference between them. Moreover, the time factor has to be considered, since both state-of-the-art automatic procedures and the manual method are usually slow. A fully automated procedure will provide more consistent results and less prone to human errors. In [9] de Weert *et al.* showed that human (inter- and intra-operator) coefficients of variation are 19% and 58%, respectively. A disadvantage of automating such an analysis is that it becomes sensitive to image noise. In the classification of tissues in noisy images, humans are more proficient than machines.

In this work we propose a novel software-based protocol for the automatic detection of the carotid artery wall contour, using edge enhancing algorithms with the final aim of overcome the weaknesses of manual inspection of CTA images. Our approach is operator independent, fast and repeatable. This work is part of the wider VASIM project carried on at Tampere University of Technology, Tampere, Finland.

2. Methods

2.1. Dataset and manual segmentation

Four patients undergoing carotid artery endarterectomy were recruited at the Tampere University Hospital (Tampere, Finland). Preoperative CTA examination was performed between the aortic arch and the vertex of the skull. In this dataset the stenosis range was [70%, 95%]. A total of 223 images were acquired depicting the plaque region present in the common and internal carotid arteries and the carotid bifurcation.

Each image meant for comparison with the automatic protocol was manually segmented by a trained operator for the outer vessel and lumen contours.

All the methodology was developed using a Dell workstation (Dell OptiPlex 9020, Windows 7 Enterprise, 64 bits, 3.10 GHz, 8.0 GB RAM) with Matlab® R2012b, Image Processing Toolbox 8.1, Signal Processing Toolbox 6.18, and Statistical Toolbox 8.1.

2.2. Automatic edge detection

Automatic segmentation was performed by processing each image using the edge enhancing protocol proposed in this article. Our approach can be summarized as follows:

(i) tissues characterized by a higher attenuation than 500 HU are assigned a new attenuation of 20 HU, intended to prevent the loss of the atherosclerotic calcified tissue. Subsequent thresholding of the image to the range [-100, 500] HU [8] allows cleaning artifacts and surrounding tissues (air, lipidic and calcified tissue);
(ii) grayscale rescaling to [0, 1] interval;
(iii) edge enhancing by the ensemble, explained in more detail below;
(iv) separating nearby objects by connected components (4 neighborhood);
(v) computing of the distance for each object to the center of the image by the *pdist2* function;
(vi) classifying the object with the smallest distance as the final outline.

In detail, the edge enhancers used in this automatic approach belong to two different categories: 5 edge detectors (Sobel, Prewitt, Roberts, laplacian of gaussian (LOG) and Canny) and 5 filters/mapping functions (laplacian filter, gradient map (GM), Otsu thresholding (OT), local range map (LRM) and standard deviation (STD) map).

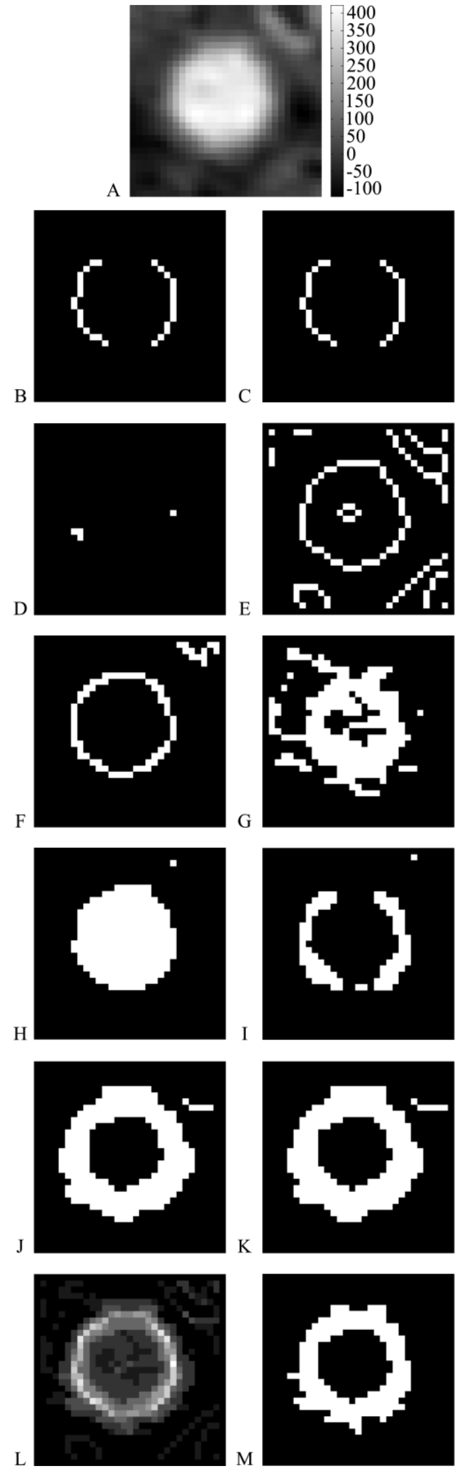

Figure 1. Edge enhancers applied to a carotid artery. A. Initial image, B. Sobel, C. Prewitt, D. Roberts, E. LOG, F. Canny, G. Laplacian, H. Otsu, I. LRM, J. GM, K. STD, L. Final contour (intersection of the initial image with the mask, M. Contour mask without lumen.

Each one of these edge enhancers was tested using a 3-pixel square window to produce an intermediate image INT_IM for each slice as follows: (i) the OT INT_IM was directly used; (ii) in LOG INT_IM a threshold of 0 was used for closed contours; (iii) LRM INT_IM was binarized using the inclusion range [0, 200]; and (iv) the 7 remaining INT_IMs were thresholded using OT. A single binary image (FUSION) was produced by fusing the 10 binary masks and thresholding using OT. An example of the application of these algorithms to a slice is represented in Fig. 1.

2.3. Comparison between manual and automatic contours

The comparison between manual and automatic segmentation of the carotid contours was done resorting to 2-dimensional correlation function *corr2* (with the manual contour as the ground truth). Each edge enhancer was also correlated individually with the manual mask. The three highest performing edge enhancers (GM, LRM and STD) were used to create a new ensemble (3M).

3. Results and discussion

The average time per image for FUSION was 0.034 s and for 3M 0.015 s. For manual segmentation the processing time for the outer contour and lumen was, in average, 5 s/slice.

Fig. 2 illustrates the three stages of the carotid contour protocol: the initial image fed to the edge enhancer algorithm (Fig. 2.A), the binary mask obtained with FUSION (Fig. 2.B) and the final segmented carotid contour (Fig. 2.C) as a result of the algorithm. The slice in Fig. 2 represents a section above the carotid bifurcation where the vessel walls haven't been separated enough to be segmented into three independent objects.

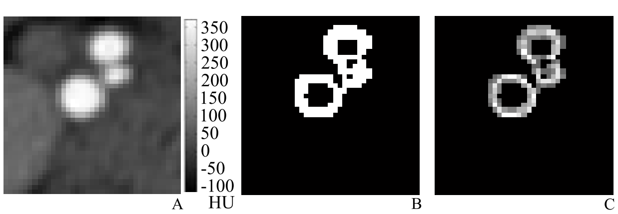

Figure 2. Carotid artery contour enhancing protocol step images. (internal carotid, lower element; external carotid, higher element; branching from the external carotid, middle element). A. Initial image; B. Contour mask without lumen; C. Final contour (intersection of the initial image with the mask).

Table 1. Performance (correlation) of the edge enhancers ensemble FUSION and 3M.

Patient	FUSION	3M	Increase
1	0.64	0.73	14%
2	0.17	0.24	47%
3	0.62	0.74	19%
4	0.51	0.60	17%
Mean	0.48	0.58	24%

The final performances (correlation between automatic and manual segmentation mask) for the four patients, using FUSION and 3M, as well as the increase of performance with 3M, are represented in Table 1.

The mean correlation coefficient between the manual and the automatic masks is 48% [17%, 64%]. By using the 3M algorithm, which presented the highest performances in the edge detection, the mean correlation is improved to 58%. This simpler (and faster) ensemble allowed obtaining a mean increase in correlation of 24%. This increase is dependent on the patient with a very wide interval ranging from 14% to 47%. This demonstrates that an approach effective for a specific patient can be non-optimal for another one.

The usage of OT for thresholding didn't provide good results, since it tends to over-threshold the objects in the image; this is clear by comparing Fig. 2 and 3 (both thresholded for 0.21 in the [0, 1] interval). This can be by the fact that the slice in Fig. 3 depicts an initial (non-homogenous) stage of atherosclerosis, as evident by the central and right bright spots (high attenuation) inside the carotid wall, that bias the optimal threshold calculation. This phenomenon didn't occur in case of a homogeneous level of atherosclerosis, advanced stage of atherosclerosis or healthy arteries.

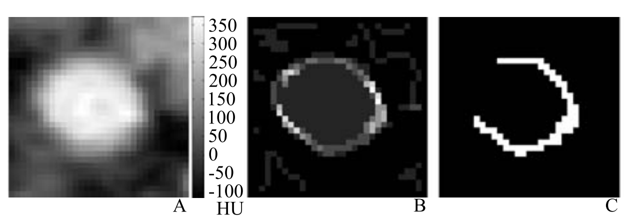

Figure 3. Extreme thresholding of the contour outline using OT. A. Initial image; B. Contour outline by FUSION; C. Final contour mask thresholded with 0.21 in the [0, 1] interval.

4. Conclusion

In this work we provide an efficient and fast method for the automatic detection of the contours of carotid arteries both in normal and atherosclerotic arteries. Our results are comparable with the manual segmented contour, as quantified by a correlation index of 58%.

Further work has to be done to improve the performance in inhomogeneous atherosclerotic plaques, such as filtering to clean abrupt changes in tissues and to select the optimal edge enhancers. GM, LRM and STD showed to be the most suitable for our purpose. Future improvements will lead to the usage of this methodology in plaque component characterization in atherosclerotic arteries.

Acknowledgements

The work presented in this paper has been partially supported by the iBioMEP national doctoral program, by the Tampere City Science Fund and by the Tampere University Hospital.

We would also like to thank iBioMEP for the travel grant given to participate in Computing in Cardiology 2014.

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