AN AUTOMATIC SEGMENTATION METHOD APPLIED TO IMAGES OF IV-OCT IN HUMAN ARTERIES WITH ATHEROSCLEROTIC PLAQUES

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Abstract: Intravascular optical coherence tomography (IV-OCT) is an imaging modality in-vivo based on the introduction of an intravascular catheter for viewing the inner wall of blood vessels with a spatial resolution of 10μm to 20μm. The acquisition and analysis of vessel images by IV-OCT are recent and enables several new applications and the development of automatic techniques of computer vision and related areas. This paper aims to describe a fully-automatic method to compute vessel's lumen area in IV-OCT images with challenges including the presence of catheters, guide wires and atherosclerotic plaques. Tests were performed in 787 human IV-OCT images presenting a mean difference in area of 0.04 mm^2 comparing with manual segmentations. The results raise the possibility that automatic methods have to perform a subsequent lumen contour correction in case of bifurcation regions.
Keywords: OCT, segmentation, intravascular, computer vision

Introduction

Optical coherence tomography (OCT) is based on the technology of low-coherence interferometry and provides cross-sectional images of tissue samples with resolution far superior to any other form of imaging modality in-vivo. This technology has many similarities with ultrasound imaging, but instead of using sound, it uses the scattering of light in the near infrared frequency as the signal source.

Intravascular optical coherence tomography (IV-OCT) is an in-vivo application of OCT based on the introduction of an intravascular catheter for viewing the inner wall of blood vessels. Several past studies evaluated the utility of IV-OCT [1]-[2], showing many advantages over other modalities such as intravascular ultrasound (IVUS), due to the resolution of 10μm to 20μm, allowing the visualization of tissues in the microscopic scale [3]. In [4] was analyzed the difference between both modalities. The acquisition and analysis of vessel's images by IV-OCT are recent and enables several new applications and the development of automatic techniques of computer vision.

Manual segmentation of structures in an IV-OCT image involves a large number of slices, which is time-consuming and operator dependent. In this paper, we propose a fully-automated method to segment coronary lumen area in human IV-OCT datasets. An evaluation was performed between a manual segmentation by an expert and the proposed automatic method using 675 slices of 5 different patients out of carina (bifurcation region) and 112 slices on carina. The discussion section shows the comparison between the results from the proposed method and other methods in the literature.

Materials and Methods

Images were collected by a Fourier-Domain OCT (FD-OCT) system (C7-XR - OCT Intravascular Imaging System, St. Jude Medical, St. Paul, Minnesota) at Heart Institute, University of São Paulo Medical School (INCOR-HC FMUSP) under the process in ethic commission CAPPesq 0243/08. We analyzed 787 frames from 5 pullbacks of 5 different patients immediately before stenting. In all datasets we had observed the presence of plaques and dissections. The input images to the proposed method were in DICOM format with dimensions 1024 x 1024 x 271 pixels with spatial resolution of 10 x 10 x 200 μm, with cartesian coordinates.

The lumen contour from each IV-OCT frame is obtained after two processes shown in Figure 1. The first is the preprocessing, which includes a removal of speckle noise, catheter and the guide-wire. The second process is a set of operations including A-lines sweeping to find high gradients on the first vessel wall.

Pre-processing – The input 2D image, represented by a cartesian coordinates system, is transformed to a polar coordinates system.

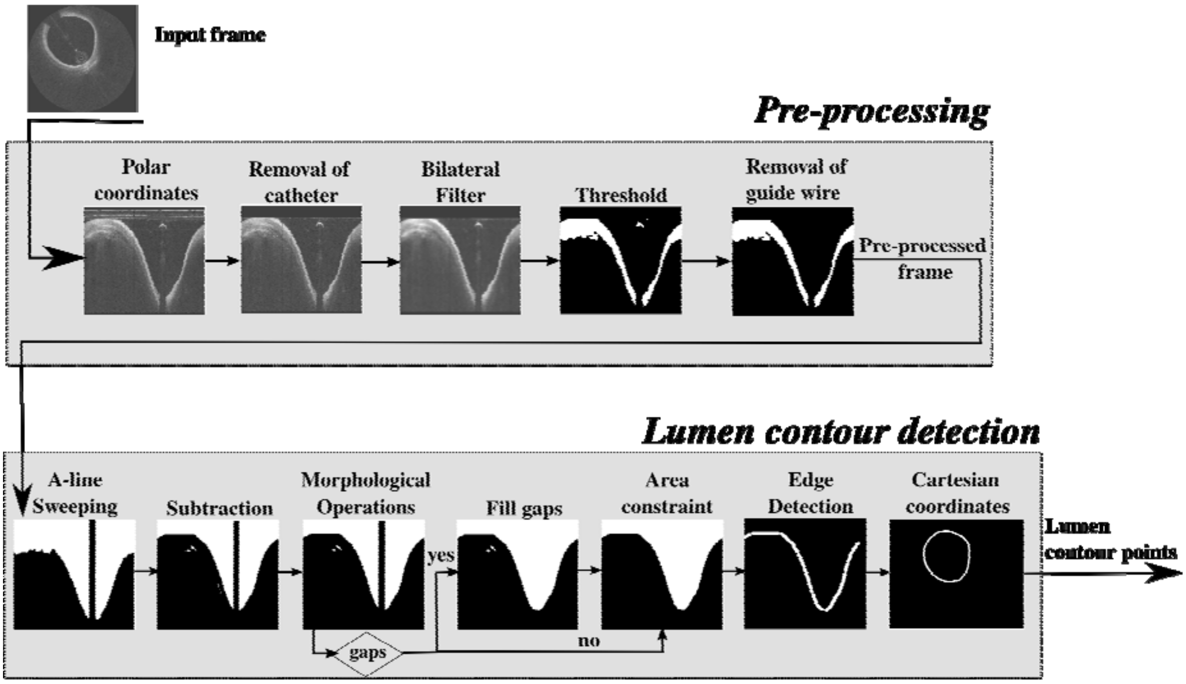

Figure 1: Scheme of the proposed method to detected lumen border.

Our catheter segmentation technique exploits the fact that the Dragonfly catheter diameter has 2.7 French (F) ~ 0.90 mm and the spatial resolution image is known. The catheter region is replaced with zero, removing the catheter sheath region from the image. As the IV-OCT image has intrinsic speckle noise, we performed a bilateral filtering [5] to smooth the image but preserving the edges.

The Otsu method [6] was used to separate the region with high gradient magnitude, which consists mainly of the first vessel-wall layer.

The Guide Wire (GW) is characterized by a bright reflection immediately followed by a shadow. Considering the GW diameter is 0.014 inches, to remove it, we applied an area constraint (only non-significant size area can be removed).

Method to detect lumen border – Based on [7], a pipeline was built to detect the lumen. Each A-line is scanned from the bottom to top of the image, until find a significant gradient. After this, the region below intima layer has value zero and the intima layer plus lumen region has value one. To segment only the lumen region, a subtraction between the image containing intima plus lumen and the first image containing only the intima layer was performed. This operation can well define irregular borders, as in the case of vessel with thrombus or dissections. To eliminate holes and shadows of any struts, a sequence of five dilations followed by five erosions was applied, the number of operations being related to the maximum degree that a shadow of a strut can occupy in the image. Since the GW shadow is always approximately 25 degrees, on the first line of the polar image, a GW shadow identification was performed searching for a horizontal gap of 20-35 pixels on the respective polar image. If a gap at the first line was identified, all corresponding A-lines were filled from top to the lumen border. Finally, the lumen border points were detected by Sobel edge detection method and the resulting polar image was transformed to an image with cartesian coordinates. A result of the lumen border detection is illustrated in Figure 2.

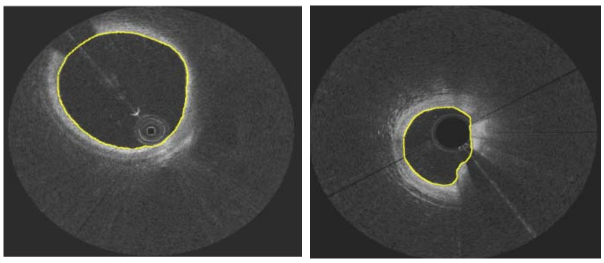

Figure 2: Result of two different lumen border detections in the cartesian coordinates system.

Validation experiments

One independent expert observer, blinded to automatic segmentation results, was involved in the manual contour tracing process, and a gold-standard was established using the *ImageJ* software. According to [8], the vessel branching is a key region for plaque evolution, so each slice was visually classified as slice in a Bifurcation Region (BR) or in a Non-Bifurcation Region (NBR). For frames in BR, the manual segmentation prioritized the tracked main artery region. An example of a manual segmentation is shown in Figure 3. A set of six metrics were used to measure the accuracy of the proposed automatic method to the lumen detection considering as reference the manual segmentation. The measures are:

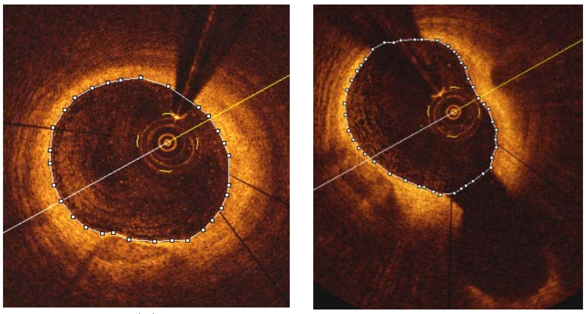

Figure 3: Manual segmentations. (a) lumen segmentation in a NBR. (b) lumen segmentation in a BR with a delineation splitting the two branches.

a) Volume overlap error (VOE):

$$VOE = \left(1 - \frac{V_m \cap V_a}{V_m \cup V_a}\right).100\%$$

b) RMS Symmetric surface distance (RMSSSD):

$$RMSSSD = \sqrt{\frac{\sum [min_{m \in M} dist(a,m)]^2 + \sum [min_{a \in A} dist(a,m)]^2}{N_a + N_m}}$$

c) Dice similarity (DSI):

$$DSC = 2.\left(\frac{|A \cap M|}{|A| + |M|}\right)$$

d) Hausdorff distance (H):

$$H = max\{max_{a \in A}\{dist(a,m)\}, max_{m \in M}\{dist(a,m)\}\}$$

e) Difference Area (DA):

$$DA = |M - A|$$

f) Accuracy (ACC):

$$ACC = \frac{(TP + TN)}{(TP + FP + TN + FN)}$$

where V_m is the segmented volume by manual method, V_a is the segmented volume by automatic method, *A* and M are the lumen area from automatic segmentation and manual segmentation in millimeters respectively, *a* is a point at the lumen contour from the manual method, *m* is a point at the lumen contour from the automatic method, N_a and N_m as the number of contour points of automatic and manual method respectively and finally *TP* is true positive, *TN* is true negative, *FP* is false positive and *FN* is false negative.

Results

The proposed algorithm was applied in 5 humans IV-OCT datasets totaling 787 frames without any user interaction and without the presence of stents. The evaluation was based on manual lumen segmentation by an expert. The results were divided in BR (112 frames) and NBR (675 frames). With the automatic method, we obtained a mean and standard deviation lumen area of 4.81±2.5 mm^2 versus 4.74±2.47 mm^2 from method for NBR IV-OCT images, with linear regression of slope 0.985, intercept 0.0008642, R^2=0.996 and p<0.001. In the case of BR IV-OCT images the mean and standard deviation lumen area was 5.85±2.35 mm^2 from automatic method and 5.16±2.06 mm^2 from manual method. Table 1 shows all metrics computed from the proposed automatic method and Figure 4 shows the relative difference between the manual vs. automatic method for NBR slices according to Bland-Altman statistics.

The manual segmentation of a slice took approximately 60 seconds. On the other hand, the processing time of automatic lumen segmentation for a slice took approximately 15 seconds considering a machine with CPU i7-3.46 GHz and RAM memory of 32 GB.

Table 1: Results of automatic algorithm and manual assessment compared together.

Automatic x Manual	Non-bifurcation slices	Bifurcation slices
n. slices	675	112
VOE (%)	4.4± 2.7	16.0±10.8
DSI (%)	97.7±1.5	90.9±7.0
H (mm)	0.13±0.09	0.76±0.53
RMSSSD (mm)	0.12±0.11	0.85±0.74
DA (mm^2)	0.04±0.03	0.27±0.21
ACC (%)	99.8±0.09	99.14±0.73

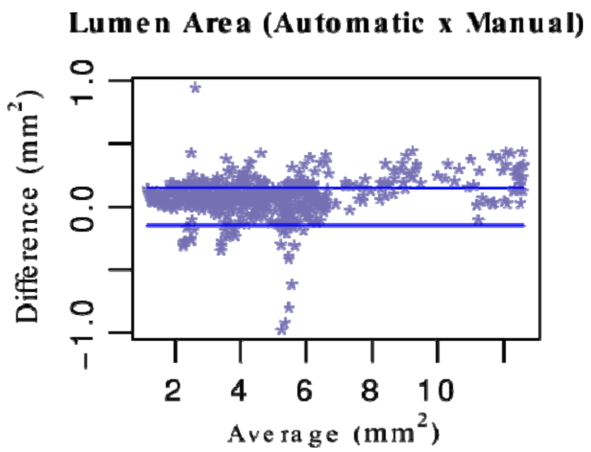

Figure 4: Bland-Altman manual vs fully-automatic method for NBR slices.

Discussion

This work shows a feasible fully automatic 2D lumen contour detector which has a similar quantitative

IV-OCT analysis to those derived manually by an expert. A computer-assisted lumen contour detection is unquestionably more practical than the use of a fully automatic method, but for research terms, involving thousand of slices, the latter one require much less expert operation time and does not suffer from possible interobserver and intraobserver-related deviations.

Considering our results for NBR IV-OCT frames of the mean lumen area of 4.81 mm^2 from automatic method and 4.74 mm^2 from manual method (a difference of 0.06 mm^2) it is possible to affirm that our results are similar to the results reported in the literature [9]–[11]. In theses reports, the difference of mean lumen area ranges from 0.04 mm^2 to 1.0 mm^2, considering 10 to 20 IV-OCT datasets. Hausdorff distance and dice similarity index were computed in [12] and [13], while VOE was computed only by [12], considering a smaller number of slices (106 - 290) than used in the present work. They have presented results as H 0.07±0.05 mm, DSI between 97.7% and 97.8% and VOE as 4.6%. Based on the previous works, our proposed method, considering NBR slices, presented a very similar DSI of 97.7% and VOE 4.4%. However, H was computed in this proposed automatic method as a higher value (0.13 mm), which means this method produces a greater discrepancy distance from manual result.

As expected, the results for BR slices are worse than for the NBR slices. The main problem is the definition of the gold-standard because the rationale of the expert is to analyze only the main vessel and consider that the side branch should not be part of the segmentation. Therefore the expert excludes the side branch creating a virtual delineation between the two branches. However, our algorithm considers the entire lumen area, which makes for a poor comparison. In order to minimize the error in BR slices it is necessary to improve the state-of-art automatic segmentation methods. It is worth noting that, as far as we know, no other work evaluated an automatic 2D lumen contour detection method on BR slices from IV-OCT images.

A more robust automatic method in BR slices could be developed to include a classification of each BR slice and a correction of the respective contours in order to delineate only the lumen area of the main vessel.

Conclusions

We have demonstrated the viability of a fully-automatic method to measure lumen area in IV-OCT images and also the necessity of identifying bifurcation regions and posterior correction of the lumen contour to limit the area of only one branch on carina.

Acknowledgements

Thanks to Sao Paulo Research Foundation (FAPESP) for the grant #13/09922-8 and Dr. Micheli Zanotti Galon for the image aquisitions.

References

[1] Yabushita, H. Characterization of Human Atherosclerosis by Optical Coherence Tomography. Circulation 106, 1640–1645 (2002).
[2] Suter, M. J., Tearney, G. J. & Bouma, B. E. Progress in Intracoronary Optical Coherence Tomography. IEEE J. Sel. Top. Quantum Electron. 16, 706–714 (2010).
[3] Prati, F. et al. Expert review document on methodology, terminology, and clinical applications of optical coherence tomography: physical principles, methodology of image acquisition, and clinical application for assessment of coronary arteries and atherosclerosis. Eur. Heart J. 31, 401–15 (2010).
[4] Finn, A. V, Chandrashekhar, Y. & Narula, J. IVUS and OCT: either or survivor. JACC. Cardiovasc. Imaging 4, 1047–9 (2011).
[5] Tomasi, C. & Manduchi, R. Bilateral filtering for gray and color images in Comput. Vision, 1998. Sixth (1998).
[6] Otsu, N. A threshold selection method from gray-level histograms. IEEE Trans. Syst. Man. Cybern. 9, 62–66 (1979).
[7] Ughi, G. J., Adriaenssens, T., Desmet, W. & D'hooge, J. Fully automatic three-dimensional visualization of intravascular optical coherence tomography images: methods and feasibility in vivo. Biomed. Opt. Express 3, 3291–303 (2012).
[8] Zarins, C.K., et al. "Carotid bifurcation atherosclerosis. Quantitative correlation of plaque localization with flow velocity profiles and wall shear stress," Circ. Res., 53, 502–514,(1983).
[9] Sihan, K. et al. Fully automatic three-dimensional quantitative analysis of intracoronary optical coherence tomography: method and Validation. Catheter. Cardiovasc. Interv. 74, 1058–65 (2009).
[10] Sihan, K. et al. A novel approach to quantitative analysis of intravascular optical coherence tomography imaging. 2008 Comput. Cardiol. 1089–1092 (2008).
[11] Tsantis, S. et al. Automatic vessel lumen segmentation and stent strut detection in intravascular optical coherence tomography. Med. Phys. 39, 503–13 (2012).
[12] Wang, Z. et al. Semiautomatic segmentation and quantification of calcified plaques in intracoronary optical coherence tomography images. J. Biomed. Opt. 15, 061711 (2010).
[13] Moraes, M. C., Cardenas, D. A. C. & Furuie, S. S. Automatic lumen segmentation in IVOCT images using binary morphological reconstruction. Biomed. Eng. Online 12, 78 (2013).