A Novel Approach to Quantitative Analysis of Intravascular Optical Coherence Tomography Imaging

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Abstract

Quantitative analysis on intracoronary optical coherence tomography (OCT) image data (e.g. QOCT) is currently performed by a time-consuming manual contour tracing process in many individual OCT images acquired during a pullback procedure (frame-based method). In order to get a more efficient quantitative analysis process and to investigate the possibilities to use this contour information for development of an image-based retrospective OCT-gating method, as a first step a novel approach has been developed that exploits a full-automated contour tracing method for coronary lumens in OCT images without the need for intensive observer related actions.

This study presents this new method, which was tested on in-vivo acquired human coronary OCT image data of 10 randomly selected patients.

1. Introduction

The recent rapid developments in catheter based OCT technology have led to great enthusiasm towards applying this technique for the imaging of coronary artery disease and applying it to the evaluation of new therapeutic interventions. The major advantage of OCT over the current reference method for intracoronary imaging, intracoronary ultrasound (ICUS), is its exceptionally high image resolution, close to that of the golden standard of histopathology, i.e. lateral and axial resolutions of 15 and 25 µm respectively. In contrast, ICUS offers lateral and axial resolutions of 120 and 80 µm respectively [1]. To be able to select OCT for such evaluation purposes, quantitative analysis tools are imperative. The measurement accuracy of QOCT has been validated and showed a good correlation both with *ex-vivo* human coronary artery specimens as well as with *in-vivo* acquired OCT data [2]. The latter is far more tempting, since the imaging of the coronary vessel wall is impossible with OCT due to the presence of blood. The vessel must be occluded with a non-dilating balloon first and than flushed with saline, before OCT imaging becomes possible. Furthermore, induced motion artifacts caused by the cardiac cycle do not only cause in-plane artifacts (resulting in a sort of corkscrew appearance of the lumen contour) but also cause the saw-tooth shaped appearance of the coronary vessel wall. This limits the possibility of using reconstructed longitudinal views of the pullback OCT image dataset for contour detection, which would be much faster than analysis of each individual image [2]. Most acquired OCT image data sets contain multiple hundreds of frames. To analyze all frames is a time costly and tedious procedure currently taking up to multiple hours. Therefore many observers only analyze 1 frame per mm, randomly selected throughout the cardiac phase. This could result in a diminished accuracy for quantitative analysis.

To reduce the workload and to improve the accuracy by eliminating possible observer-related induced measurement inaccuracies, we investigated the possibility and feasibility of developing a fully automatic lumen contour detection approach. The newly developed method has been tested on *in-vivo* data of 10 patients with as reference method computer-assisted observer detected contours.

2. Methods

2.1. OCT imaging

We used OCT images acquired with a commercially available system (Lightlab Imaging, Westford, MA, USA). The light source was a 1310-nm broadband super luminescent diode with an output power in the range of 8.0 mW. The penetration depth in the tissue was approximately 1.5 mm. The imaging catheter (Imagewire™ Lightlab) had a maximum diameter of 0.019 inch and contained a single fiber optical core within a transluminent sheath. The wire was pulled back automatically at a speed of 1.0 mm/s while images were acquired at a rate of 15 frames/s. The acquired studies were saved in AVI format, and were then converted to DICOM by in-house developed dedicated software.

Currently the OCT data still comes in different digital formats.

The developed fully automated OCT contour detection method contains the following steps:

2.2. Pre-processing

After importing the digitally stored OCT image data, a pre-processing filtering step is applied to every individual OCT image (Fig 1A). The primary goals of this step are to reduce speckle noise inherent in OCT data and to take care of gaps and shape irregularities in the blood-lumen interface. The preprocessing step consists of a combination of gaussian filtering and relative thresholds to remove speckle noise, morphological closing to remove gaps and contrast stretching to ensure that the image is properly normalized.

2.3. Edge detection

The basic algorithm used to detect all coronary vessel edges that can be found within a single OCT image, including the lumen edge (or boundary), is the Canny filter [3]. However, due to the rapid changes of the lumen morphology between sequential OCT images, a straightforward application of the Canny filter does not directly lead to the desired result. Furthermore, there is a large difference between the OCT datasets acquired from different individuals. To tackle these problems, the Canny filter is implemented iteratively using a binary search, until the desired percentage of image pixels are classified as edge pixels (Fig. 1). So the threshold of the Canny filter is increased or decreased depending on the amount of detected pixels.

2.3. Lumen edge selection

Not all edges detected by the Canny filter are on the lumen contour. Some edges are from noise caused by the catheter and some edges are from speckle noise. Even after the applied pre-processing some speckle noise will still be present in the images. Some parts of the contour may also not be visible or are not pronounced enough to produce an edge. In practice this is not such a problem judging by the fact that most contours are closed and clearly visible. The Canny filter also detects edges which do not belong on the lumen contour. These edges are removed using the dot product between the gradient orientation and the catheter center. So every pixel where this dot product is larger than a certain threshold is removed (fig. 1D). However, some erroneous edges are still present. The majority of these edges are short so a threshold by length is used to remove these edges. The subset of edges, which will be selected from the remaining edges, is the one providing with the highest quality score of all possible combinations. The quality parameter is determined by the area-, length- (relative to the area) and the gaps in the contour.

2.5. Post-processing

The pre-processing step sometimes pushes the edges detected with the Canny filter away from the lumen contour. In order to put the edges back on the lumen contour a post-processing step is applied. This step pushes contour points outwards based on the image gradient magnitude and a local search of 5 pixels. The contour is smoothed based on the radius length, weighting neighbour coordinates applying the gradient magnitude and the euclidean distance with a normal distribution.

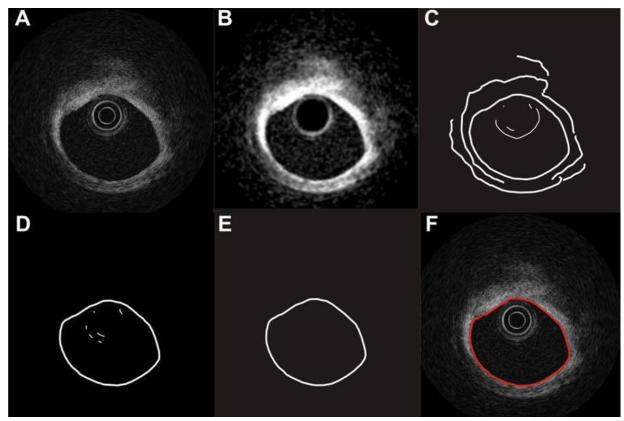

Figure 1. Panel A, shows an original OCT image. In panel B, the result of the pre-processing step can be appreciated and in panel C the edges diction results of the Canny filter. Panel D, shows the lumen contour edge selection and panel E the result after a threshold by edge length. Finally the lumen contour is presented in panel F.

3. Results

The new method was evaluated on 10 *in-vivo* acquired OCT pullback datasets of human coronary vessels. Every individual image was analyzed by a human observer using a computer-assisted software (Vessel analysis, CURAD BV, Wijk bij Duurstede, The Netherlands) and was used as reference method [2].

In these 10 datasets 1890 individual OCT images were available. The manual analysis required several hours and the automated method approximately 30-45 min (Fig. 2), resulting in a processing time of between 2-5 sec per frame, depending on the image resolution. Of the 1890 automated detected lumen contours, 10 (0.5%) showed a large deviation as compared to the manual contours. The deviations were mostly caused by artifacts in the images, such as reflections of the outer sheath of the catheter. For possible necessary manual correction a graphical user interface is available.

The mean lumen areas of the 10 cases as measured by the human observer were 4.1±1.4 mm^2 and with the automated method 4.0±1.3 mm^2; $p=0.09$ (calculated by a student's t-test), respectively.

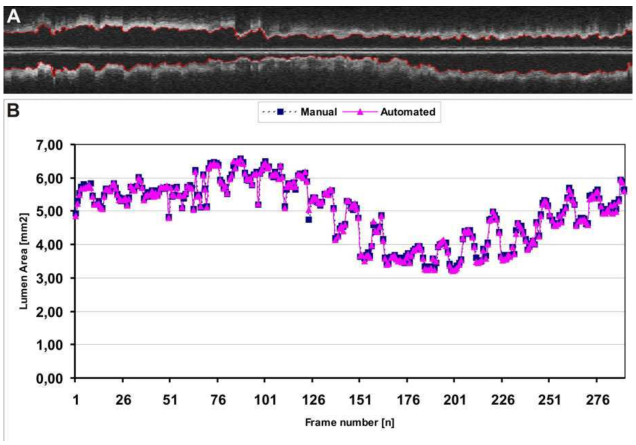

Figure 2. Panel A, shows a longitudinal reconstruction with the lumen contour presented on top of a total pullback procedure. Panel B shows the lumen area results of both methods.

Furthermore, linear regression analysis showed a good correlation between the methods (Fig. 3).

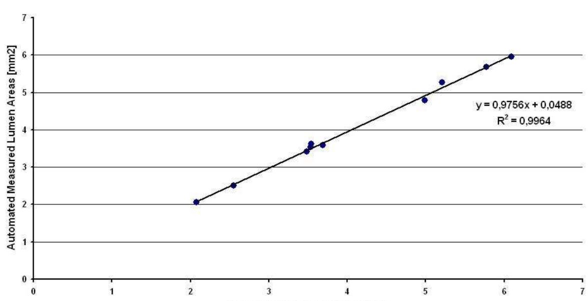

Figure 3. Linear regression analysis of the 10 cases.

Finally, also a Bland-Altman analysis showed good results without any outliers and with a mean relative difference between the methods of –1.14±1.87% (Fig. 4).

4. Discussion and conclusions

This study shows that the fully automated lumen contour detection of *in-vivo* human coronary OCT image data is feasible by showing similar results as a human observer without statistical significant differences.

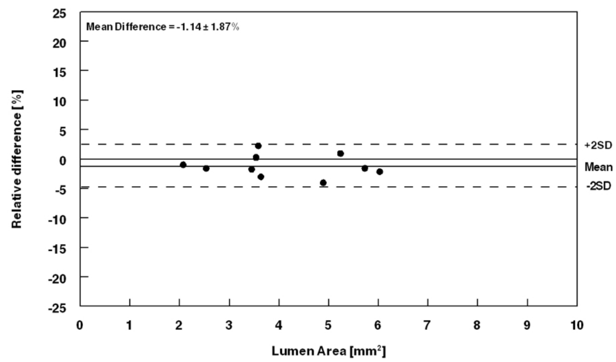

Figure 4. Bland-Altman analysis of the 10 cases.

However, there is a small tendency, resulting in a small systematic deviation, for the automated method to position the contour more at the inside of the lumen than on top of it, which seems to be the preference of the human observers. Since this is a systematic deviation, it plays no role in analysis of longitudinal studies and it was also not statistically significant.

To our knowledge this is the first fully automated OCT lumen contour detection method described. Although the number of cases used for this feasibility study is a bit on the low side, the results are promising. Although the fully automated method needs a check for deviated frames, the number of these false detected lumen contours is relatively very low (e.g. 0.5%). Furthermore, the applied quality score easily identifies those frames, so a complete visual check of all analyzed frames is not necessary.

The advantages of a fully automated contour detection method are the fast analysis time as compared to the manual method, although computer-assisted, and of course there are no inter- and intra-observer related possible deviations. Furthermore, the results of a fully automated lumen contour detection offer the possibility to use this for retrospective image-based OCT-gating. As can be appreciated in figures 2 and 5, the artifacts induced by the cardiac cycle cause a saw-tooth shaped appearance of the coronary vessel wall.

Since most cardiac imaging methods are gated it would be desirable to have also the possibility to gate OCT data since it improves not only the visual appearance (e.g. a smooth representation of the vessel wall providing a better matching with other imaging modalities as ICUS or multi-slice computed tomography (MSCT)) but also improves measurement accuracy [4]. Since OCT is becoming a popular choice for first-in-man trials for the evaluation of new therapeutic interventions, accuracy is of utmost importance.

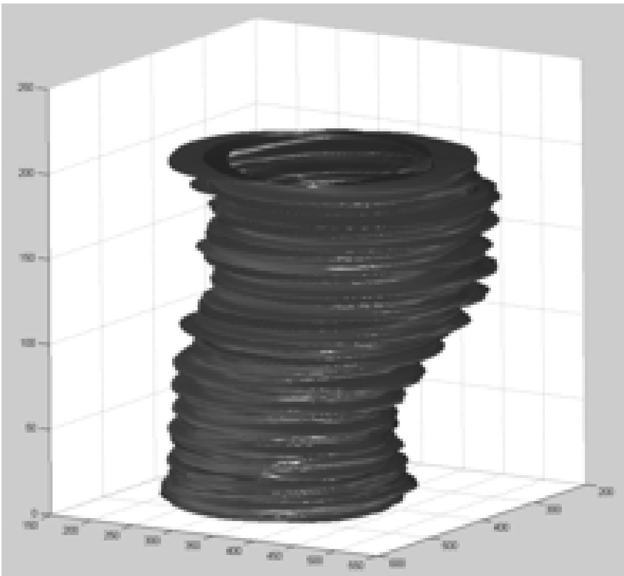

Figure 5. A 3D-plot of all full-automated detected lumen contours of 1 of the analyzed cases.

Previous studies have shown that OCT and QOCT are valuable additional imaging tools to the currently applied reference method for intravascular coronary imaging, ICUS. The advantages of OCT have been mentioned in the introduction. However, the current disadvantages are the necessary temporal closure of the vessel to be able to flush it with saline before the vessel wall can be imaged, and the low penetration depth limiting the visualization of the outer vessel borders in areas with severe amounts of plaque and finally cardiac motion induced artifacts. Retrospective image-based gating of which the current study was the first step could possibly solve the problem of motion artifacts [5].

For the first two problems, new systems are currently being developed and are in a research phase. They make use of the optical frequency domain imaging (OFDI) technique, allowing acquisition of images at the very high frame rate of approximately 125 frames/s. By pulling the catheter back at speeds of 15-25 mm/s at this high frame rate, the vessel does not need to be occluded anymore. However, these new advantages also bring new disadvantages. One of them is that in this way acquisition of images is performed during a few complete cardiac cycles bringing together images acquired at diastole and systole and everything in between. With the coronary lumen area changing on average 10% during the cardiac cycle this could lead to deviated results. This could limit the application of the OFDI technique in longitudinal atherosclerosis progression-regression trials. The current OCT technique combined with the possible application of gating could therefore provide a better platform when performing multi-modality imaging studies comparing the OCT image data against gated ICUS and gated MSCT data.

The present study shows that fully automated lumen contour detection in OCT images is feasible with a small number of frames showing easily correctible artifacts. The described method could be the first step towards a retrospective image-based OCT-gating method.

References

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