Iterative Otsu's method for OCT enhanced delineation in the aorta wall

Daniel Alonso[a], Eusebio Real*[a], José Fernando Val-Bernal[b], José M. Revuelta[c], Alejandro Pontón[d], Marta Calvo Díez[d], Marta Mayorga[b], José M. López-Higuera[a], Olga M. Conde[a]

[a]*Photonics Engineering Group, Dep. TEISA, University of Cantabria, Plaza de la Ciencia sn, 39005 Santander, Spain,* [b]*IDIVAL and Anatomical Pathology Department, Marqués de Valdecilla University Hospital, Medical Faculty, University of Cantabria, Avda.Cardenal Herrera Oria S/N 39011, Santander, Spain,* [c]*Medical and Surgical Sciences Department. Faculty of Medicine. University of Cantabria Avda.Cardenal Herrera Oria S/N 39011, Santander, Spain,* [d]*Cardiovascular Surgery Service. Marqués de Valdecilla University Hospital, Av Valdecilla, 25, 39008 Santander, Spain*

ABSTRACT

Degradation of human ascending thoracic aorta has been visualized with Optical Coherence Tomography (OCT). OCT images of the vessel wall exhibit structural degradation in the media layer of the artery, being this disorder the final trigger of the pathology. The degeneration in the vessel wall appears as low-reflectivity areas due to different optical properties of acidic polysaccharides and mucopolysaccharides in contrast with typical ordered structure of smooth muscle cells, elastin and collagen fibers. An OCT dimension indicator of wall degradation can be generated upon the spatial quantification of the extension of degraded areas in a similar way as conventional histopathology. This proposed OCT marker can offer in the future a real-time clinical perception of the vessel status to help cardiovascular surgeons in vessel repair interventions. However, the delineation of degraded areas on the B-scan image from OCT is sometimes difficult due to presence of speckle noise, variable signal to noise ratio (SNR) conditions on the measurement process, etc. Degraded areas can be delimited by basic thresholding techniques taking advantage of disorders evidences in B-scan images, but this delineation is not optimum in the aorta samples and requires complex additional processing stages. This work proposes an optimized delineation of degraded areas within the aorta wall, robust to noisy environments, based on the iterative application of Otsu's thresholding method. Results improve the delineation of wall anomalies compared with the simple application of the algorithm. Achievements could be also transferred to other clinical scenarios: carotid arteries, aorto-iliac or ilio-femoral sections, intracranial, etc.

Keywords: OCT, aortic wall degradation, ascending thoracic aorta, Otsu's method

1. INTRODUCTION

Surgical repair of ascending thoracic aneurysms usually involves the substitution of the diseased portion of the aorta by a graft, which has to be sewn onto both cut ends to replace the degraded vessel section that is removed [1]. The thoracic aortic graft has to be sewn to the closest healthy tissue adjacent to prevent further medical complications.

The aorta is structured in three different layers: intima, media and adventitia [2]. The media layer provides strength and elasticity to the wall mainly due to Smooth Muscle Cells (SMC) and an organized matrix of collagen and elastin fibers. The degradation of the media aortic layer has been documented as the main cause for the formation of an aneurysm [3], which can lead to death if it suffers from a dissection.

Optical Coherence Tomography (OCT) can be applied to visualize tissue within depth of few millimeters, enabling to see a region of the media layer [4]. Anomalous tissue regions produce different backscattering intensity profiles when imaged with OCT due to the invasive appearance of acidic polysaccharides and mucopolysaccharides within a typical ordered microstructure of parallel lamellae of smooth muscle cell, elastin and collagen fibers.

The goal of this proposal is to generate an OCT delimitation of wall degradation upon the spatial quantification of the extension of degraded areas, in a similar way as conventional histopathology can assess healthy or diseased conditions based on the extension of degraded tissue regions [3]. This proposed OCT process can offer a real-time clinical insight of

*eusebio.real@unican.es; phone 34 942 200 877 +12; http://gif.teisa.unican.es/

the vessel status to help cardiovascular surgeons in vessel repair interventions. However, the delineation of degraded areas on the B-scan image from OCT is sometimes difficult due to presence of speckle noise, variable SNR conditions on the measurement process, etc. Degraded areas could be outlined by basic thresholding techniques taking advantage of disorders evidences in B-scan images, but this delineation is not always optimum and requires complex additional processing stages [5].

This work proposes an optimized delineation of degraded spots in vessel walls, robust to noisy environments. The delineation is based on the iterative application of Otsu's thresholding method of the reflectivity intensity to determine the type of local structure [6]. OCT B-scans present dark regions due to low backscattering areas of tissue, corresponding to constituents degradation (SMCs, elastin, collagen) and emergence of acidic polysaccharides. Results improve the delineation of wall anomalies providing a deeper physiological perception of the vessel conditions. Achievements could be also transferred to other clinical scenarios: carotid arteries, aorto-iliac or ilio-femoral sections, intracranial, etc.

2. MATERIALS AND METHODS

OCT setup

The OCT imaging system is the swept source OCS1300SS from Thorlabs. It provides depth penetration up to 3mm in air, with a resolution of 12µm x 25µm (axial x lateral), digitalized with 512 pixels x 1024 pixels. The outcome of the OCT are B-scans, which consist on cross-sectional images within the sample tissue. Provided images are digitalized with 8 bits intensity representation, corresponding to a dynamic range up to 100dB, in the present work, typical value obtained is around 50dB.

Aorta specimens

Aorta samples analyzed in this work correspond to 28 patients, presenting Thoracic Aortic Aneurysm (TAA) repair interventions (18 patients) and to heart donors (10 patients). All specimens correspond to the Ascending Thoracic Aorta (ATA) region and were analyzed ex-vivo. Samples were divided into different regions and interrogated focusing the optical probe on the surface, here the intima layer. After the OCT interrogation procedure, samples were analyzed applying common histological staining procedures, in order to correlate degradation seen in the OCT B-scans with real degradation events.

Health condition of aorta specimens is strictly linked to the degradation extension of SMC and elastin [3]. This degradation can be seen and precisely evaluated through histological imaging, being the amount and extension of anomalies linearly related to the arterial wall structural wellness. Every sample can be then assigned a degradation score, corresponding to degradation quantification [3, 5]. Aortic samples can be classified into two different risk categories according to this quantification score: lowly degraded and severely degraded [5].

Anomaly detection

The analysis of aorta samples is focused on the media layer. OCT B-scans typically exhibit speckle-like noise and reflection artifacts. In addition, aortic tissue presents strong attenuation, what requires a compromise between penetration and SNR, which typically results in the addition of noise to the image. The proposed method is intended to delineate anomalous regions, detecting its border with the surrounding healthy tissue. A typical filtering procedure would deteriorate precise delineation.

Otsu's method [6] is intended to automatically binarize an image based on the intensity histogram of its pixels. It is based on the assumption of having two classes of data in the image: the pixels of the background and the pixels of the foreground. The algorithm iteratively varies the binarization threshold, calculating the variance of each class. The optimum threshold is the one that minimizes the variance of the two classes, i.e., the one that maximizes the variance among the two classes. In the case of aortic tissue, the foreground corresponds to high backscattering intensity produced by healthy tissue. The background corresponds to regions of low backscattering, produced in the air region above the image. Other parts of the image that contribute to the background are the deepest region within tissue and the pathological degenerations present among the healthy tissue.

The main inconvenient for a direct application of Otsu's method is the great amount of dark pixels occurrence, corresponding to air and deep regions, what distorts image intensity levels and threshold performance. For this reason, a first segmentation step is necessary (Fig. 1). The original image is filtered with a strong median filter and then the Otsu's method is applied. This initial process provides a binary segmentation mask that will be applied to the original (non-filtered) image, focusing the incoming analysis on the desired region.

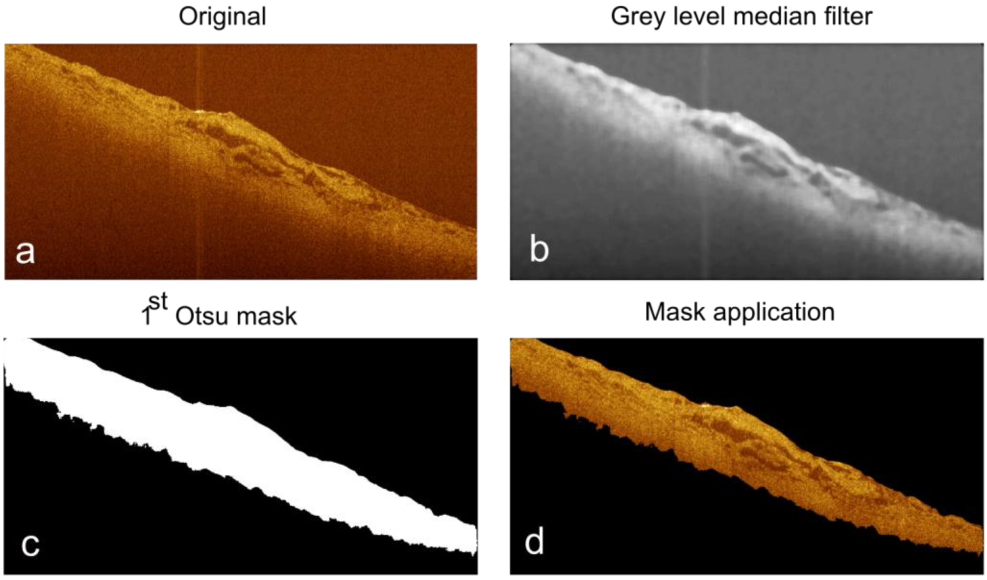

Figure 1. First application of Otsu's thresholding method. The original image (a) is firstly converted to greyscale and filtered with a strong median filter (b). The application of Otsu's method to the filtered image produces a segmentation mask (c) used to delimit the region under analysis (d).

After this first step, the region under analysis is reduced to the region that coincides with the binary mask. This leaves a clearer histogram (Fig. 2a), ideal for Otsu's thresholding procedure. The following steps are iterations, consisting on the application of Otsu's method to the previously masked region (Fig. 2b), obtaining again a new mask for the incoming step. This reduces iteratively the region under analysis towards anomalies detection.

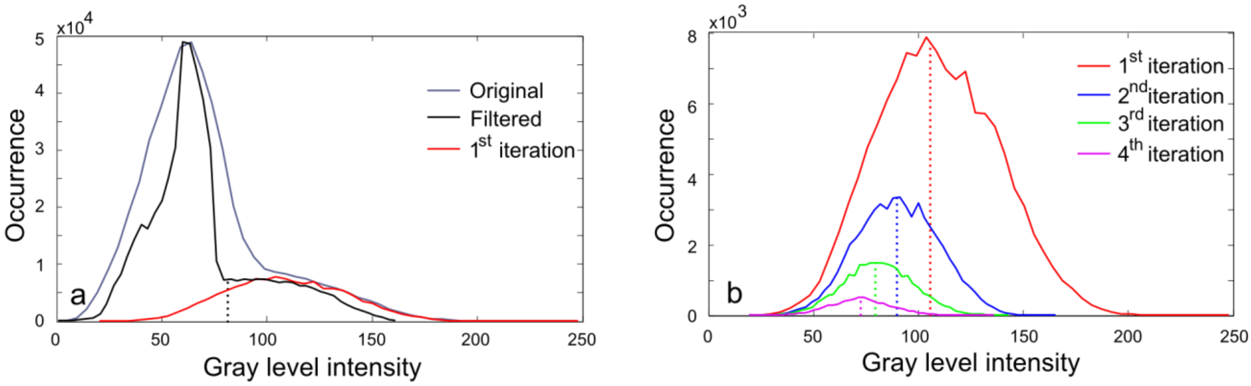

Figure 2. Histogram representation of image regions under analysis during the process (solid lines) and corresponding Otsu's thresholds (dashed lines). The filtering process to obtain the first Otsu threshold modifies the original image histogram (a). The rest of Otsu iterations (b) only require Otsu's method iterations.

3. RESULTS

The performance of Otsu's method is dependent on the shape of the histogram. According to Fig. 2a, the filtering process strongly affects the original image histogram, removing intensity counts corresponding to noise and improving the segmentation threshold procedure. This leaves two well differentiated regions in the histogram perfectly divided by the application of Otsu's algorithm. After the first segmentation (Fig. 3a, 3b), the intensity occurrence of low intensity pixels is strongly reduced, as this part of the histogram is due mostly to the upper, air region and bottom, low sensitivity regions. The remaining region of the image leaves a completely different histogram for the 1st iteration, with an order of magnitude less occurrence and different shape (Fig. 2a). For the rest of iterations, the histogram shape is similar (Fig. 2b). It can be seen how the threshold obtained by Otsu's method on each iteration moves towards lower gray intensity levels. This is due to the fact that, on each iteration, the remaining part of the image is focused on the anomaly regions, those presenting low backscattering intensity levels.

After the first segmentation (Fig. 3a, 3b), each Otsu iteration is applied only to the region of the original image corresponding with the previous mask. The effect of the second to fourth iterations is shown in Fig. 3c-3h. These iterations provide isolation and reduction of low reflectivity regions, improving delimitation of the areas affected by the structural degradation.

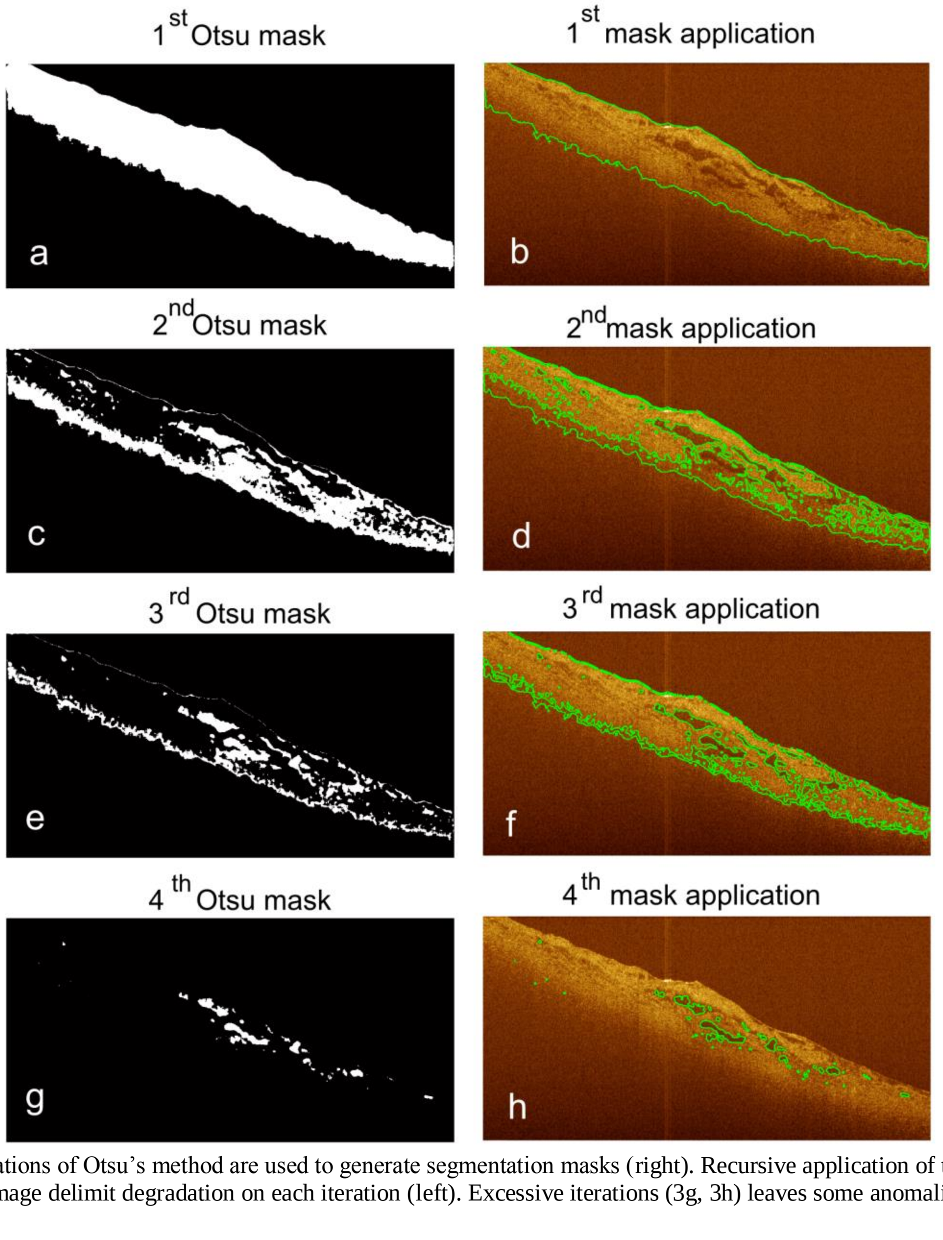

Figure 3. Iterations of Otsu's method are used to generate segmentation masks (right). Recursive application of the masks to the original image delimit degradation on each iteration (left). Excessive iterations (3g, 3h) leaves some anomalies undetected.

Each consecutive iteration highlights the anomalies present on the media wall with improved accuracy. The number of needed iterations depends on the image intensity variations and the expected results. In the case of this work, the number of required iterations for the whole set of samples is three. If more iterations are processed, the algorithm will look for anomalies inside the anomaly itself, leaving brighter anomalies undetected (Fig. 3g, 3h). Once the number of iterations has been tested for an image, given the tissue and configuration, the whole samples set is processed correctly with the same number of iterations.

The proposed algorithm is applied to the two samples set considered: lowly degraded and severely degraded specimens (Fig. 4). The same parameters have been maintained for all the samples. In the case of severe degradation, big areas are identified by the algorithm, corresponding to the degradation areas (Fig. 4b, 4d, 4f). In the case of lowly degraded samples, small areas are detected (Fig. 4a, 4c, 4e). These areas correspond to low intensity spots, in this case due to the effect of noise or small inhomogeneities in tissue composition. However, these anomalies are smaller and less numerous, corresponding with the expected physiological and structural condition of the artery wall.

A relevant parameter for the performance of the algorithm is the SNR of the image. This affects the dynamic range and in consequence, the intensity histogram of the image. The effect of the dynamic range can be seen in the brightness of the air region and the deep low sensitivity region. The first step of the algorithm is intended to mitigate this effect and the variation among samples. Fig. 4b presents more noise than Fig. 4d and Fig. 4f, however, anomalies are detected in the three cases.

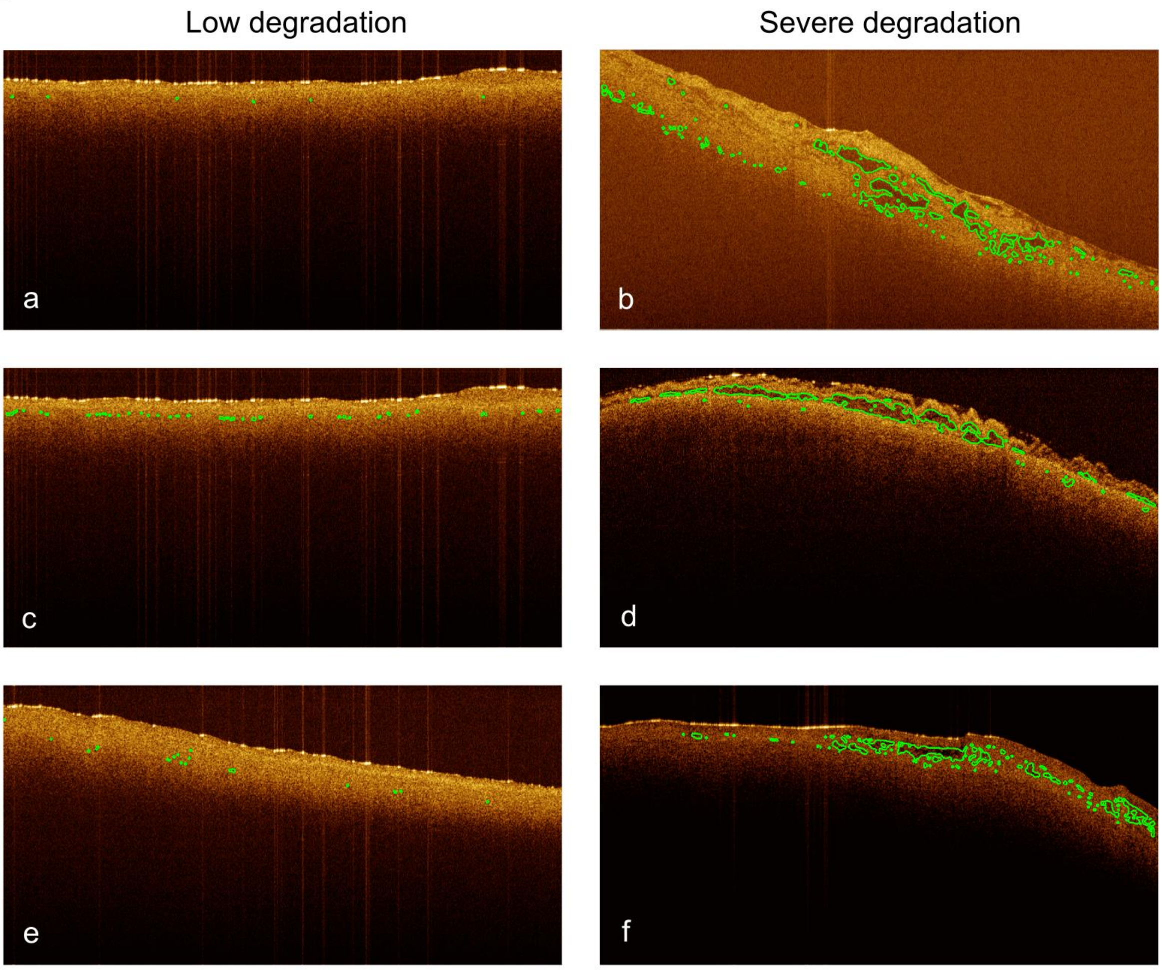

Figure 4. Comparison of detected regions in the case of a low degradation specimens (a, c, e) and a severe degradation specimen (b, d, f).

4. CONCLUSION

An iterative implementation of Otsu's method for thresholding has been implemented for segmentation purposes in OCT images of aortic wall tissue. The proposed algorithm is based on the iteration of the mentioned method, upon the consecution of the expected features. In the case of aorta images, a number of three iterations allows identifying different regions according to backscattered intensity, simplifying the procedure to establish an anomaly detection threshold [5]. The application of an optimal threshold allows identification of reflectivity inhomogeneities, intimately linked to differences in tissue composition, what can be of use for diagnostic purposes. The proposed algorithm is simple and computationally inexpensive, as it consists on the obtention of variances (Otsu's method), a median filter and 'AND' operations with obtained masks. This makes the algorithm fast and hence, a feasible implementation for future in-situ implementations under real time surgery conditions.

Future application of this segmentation procedure can assess determination of artery degradation, to be compared with common histological procedures [1]. In low degraded samples, anomalies have small dimension whilst in the cases of high degradation, areas tend to be larger (Fig. 4) and more numerous. Ultimately, diagnosis can be simplified to a computation of the areas of the anomalies detected in the samples.

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