Enhanced delineation of degradation in aortic walls through OCT

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ABSTRACT

Degradation of the wall of human ascending thoracic aorta has been assessed through Optical Coherence Tomography (OCT). OCT images of the media layer of the aortic wall exhibit micro-structure degradation in case of diseased aortas from aneurysmal vessels or in aortas prone to aortic dissections. The degeneration in vessel walls appears as low-reflectivity areas due to the invasive appearance of acidic polysaccharides and mucopolysaccharides within a typical ordered microstructure of parallel lamellae of smooth muscle cells, elastin and collagen fibers. An OCT 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 offers a real-time clinical insight 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 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. This work proposes an optimized delineation of degraded spots in vessel walls, robust to noisy environments, based on the analysis of the second order variation of image intensity of backreflection to determine the type of local structure. Results improve the delineation of wall anomalies providing a deeper physiological perception of the vessel wall conditions. Achievements could be also transferred to other clinical scenarios: carotid arteries, aorto-iliac or ilio-femoral sections, intracranial, etc.

Keywords: OCT, thoracic aorta aneurysm, Frangi's filter, 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 sewing point of the thoracic aortic graft has to be the closest adjacent healthy tissue to prevent further medical complications: dissections, pseudo-aneurysm formation, etc.

The aorta is a cardiovascular vessel which wall is structured in three different layers: intima, media and adventitia [2]. The media layer provides strength and elasticity to the wall due to 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] that, if it suffers from a dissection, it can lead to death.

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.

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The goal of this proposal is to optimize the delineation of anomalies that appear in the media layer of the aortic wall. Moreover, the generation of an OCT indicator of wall degradation upon the spatial quantification of the extension of degraded areas, in a similar way as conventional histopathology [3], will be also addressed. This proposed OCT marker offers a real-time clinical insight 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 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 analysis of the second order variation of the reflectivity intensity to determine the type of local structure [6]. In previous research works, this procedure has been applied to highlight small blood vessels seen as dark tubes in an image [6]. In a similar way, OCT B-scan images present dark regions due to the low backscattering areas of tissue associated with anomalies appearance. These regions correspond to components degradation (SMCs, elastin, collagen) and emergence of acidic polysaccharides.

2. MATERIALS AND METHODS

2.1 Aorta specimens and OCT measurements

The OCT imaging system is the swept source OCS1300SS from Thorlabs. It provides a dynamic range up to 100dB and in depth penetration up to 3mm in air. Resolution is 12µm x 25µm axial and lateral respectively. The OCT system provides B-scan images that consist on cross-sectional images within the sample tissue i.e. the aortic vessel wall.
Aortic vessel walls from human samples were studied in laboratory. These samples correspond to 28 patients distributed into those from Thoracic Aortic Aneurysm (TAA) repair interventions (18 patients) and from heart donors (10 patients). All aortic specimens come from the Ascending Thoracic Aorta (ATA) region and were analyzed ex-vivo. Tissue samples were divided into different squared regions and were interrogated with the OCT system focusing the optical probe on the inner surface of the aortic vessel, here the intima layer. After the OCT measurement process, samples were analyzed applying common histological staining procedures, in order to correlate the degradation seen in the OCT B-scans with real histological degradation events.
The analysis of aorta samples is centered on the media layer of the aortic wall. Image segmentation is required to delimit the media layer region between the air-tissue interface and the maximum penetration region with acceptable SNR information. OCT B-scans typically exhibit speckle-like noise and reflection artifacts that come to disturb the proper identification of degraded areas.

2.2 Hessian-based multi-scale filtering

A multi-scale filter [6], based on the Hessian matrix of the reflectivity profile, has been applied to identify the extension and shape of anomalous media regions. This filter is based on the computation of a function called *vesselness* [7], computed from the eigenvalues of the Hessian matrix of the OCT B-scans. The Hessian matrix is computed by convolving a Gaussian second derivate function with the desired image. The performance of the filter depends on the standard deviation of the Gaussian function (σ). The combination of different σ, provides the multi-scalar result. In other applications, this filter known as Frangi's filter [7] has been used to identify vessels of varying sizes on medical images [6]. In this case, the media wall degradation begins with disorders in its lamellae structure that resemble a vessel appearance. Fig.1 shows the whole analysis for an aneurysmal sample where the multi-scale filter allows identifying the low reflectivity areas, that appear in a direction parallel to the tissue surface, quite accurately. After the filtering application, a finally adaptive Otsu thresholding process [8] delimits the anomalous regions present in the sample.

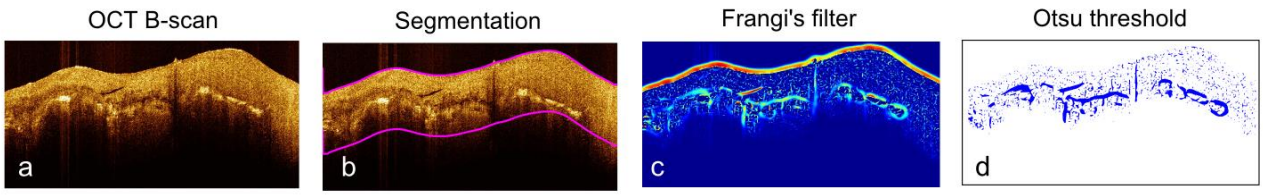

Figure 1. Delineation procedure for the anomaly delineation within the aortic media layer: (a) B-scan from the aortic wall; (b) segmentation of the aortic media layer; (c) Frangi's filtering; (d) final degradation delineation after Otsu thresholding.

3. RESULTS AND DISCUSSION

The amount and extension of anomalies seems to be linearly related to the arterial wall structural wellness. This hypothesis has been contrasted and validated against a semi quantitative pathological score of the aortic wall condition [3]. Aortic samples can be classified into two different risk categories according to their artery real degradation: low degraded and severe degraded samples. After the segmentation of the images and noise reduction, diagnosis can be performed through a simple computation of the areas of the detected anomalies as a final step after the proposed filtering and thresholding application [5]. Fig.2 shows the analysis with different σ values of two different aortic samples: a heathy aorta from a heart donor (first column) and a pathological aorta with severe degradation (second column).

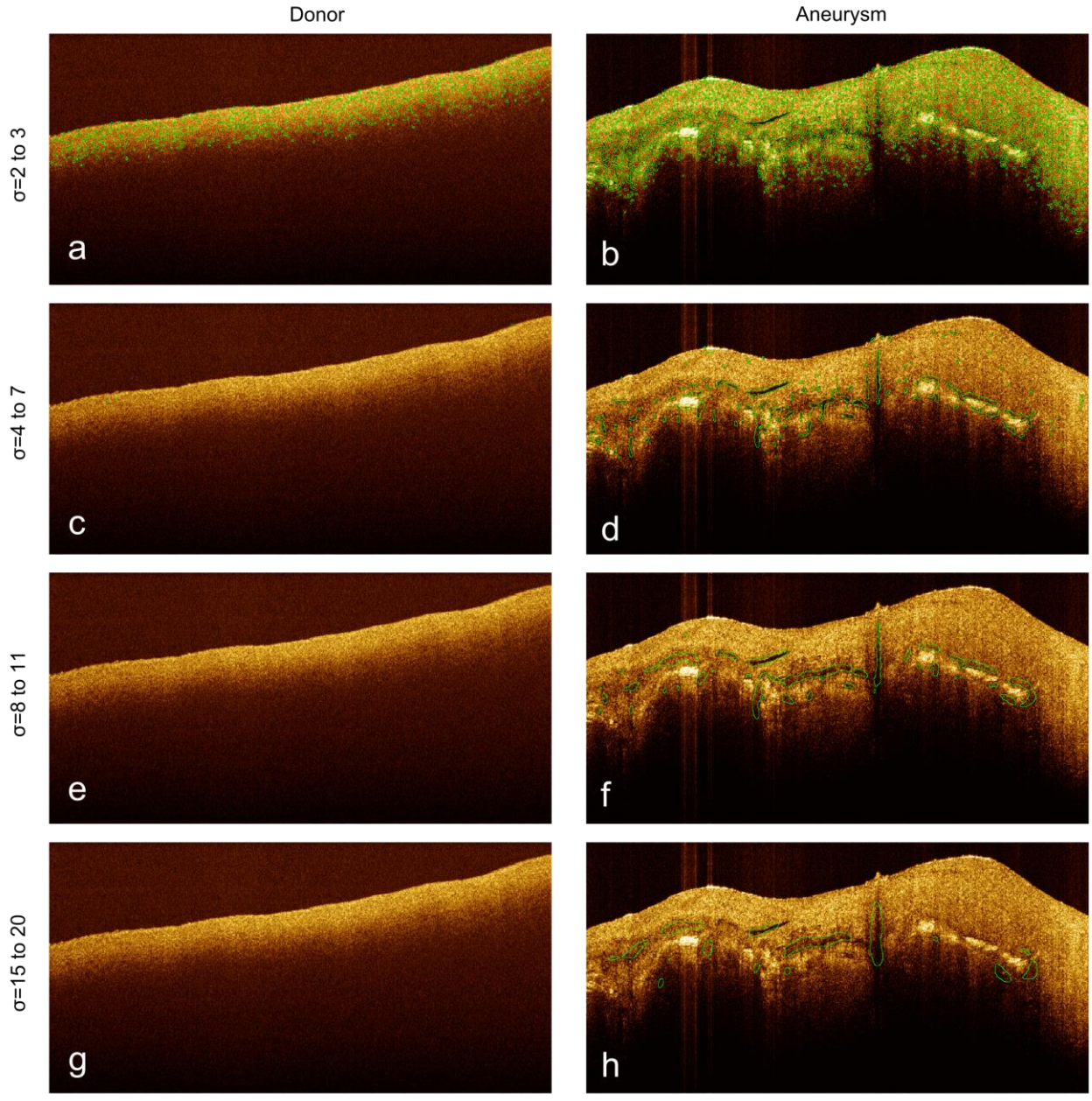

Figure 2. Anomalies, delimited in green, identified varying the σ factor of the Gaussian second derivative functions used for the Frangi's filter. Donor samples (first column) present anomalies only for small σ. Aneurysm samples (second column) present anomalies of different sizes.

The size of effects that become identified in an image is defined by the width of the convolution function, approximately 2σ. With high σ, the filter shows only the big anomalies, removing small and less relevant anomalies. This corresponds with different alterations produced in the artery wall.

The healthy aorta presents only small anomalies, which are seen applying small σ values (Fig. 2a). Detected anomalies are not due to alterations in the aorta wall, but to noise in the image and small inhomogeneities due to tissue composition. It can be considered that areas detected with $\sigma<3$ are noisy. In the case of aneurysm sample, different anomalies are identified as a function of the σ value. Small anomalies produced within a single lamellar unit (width 16.8μm, approximately 4 pixels given the OCT system resolution) will be detected with $\sigma=2$ to 8 approximately (Fig. 2b), although noise is altering the results, as in the donor case. Greater anomalies, comprising two or more lamellar units (33.6 μm or more, approximately 8 pixels) are detected with $\sigma=8$ approximately (Fig. 2d). This can be associated with cystic change and elastic fragmentation in the wall [3, 5]. Anomalies comprehending wide areas (Fig. 2f, h), are associated with fibrosis and necrosis. However, when σ is increased considerably, the effect of the strong filtering process can distort the border of detected areas (Fig. 2h).

Results shown for different σ can be coupled to produce a multi-scale result including all the anomalies found with the different dimensions. This superposition, and the application of Otsu's method (Fig. 3 c, f), delineates more accurately the wall degradation in the case turbid media such as the aorta wall than conventional threshold techniques based on the histogram (Fig. 3 b, e).

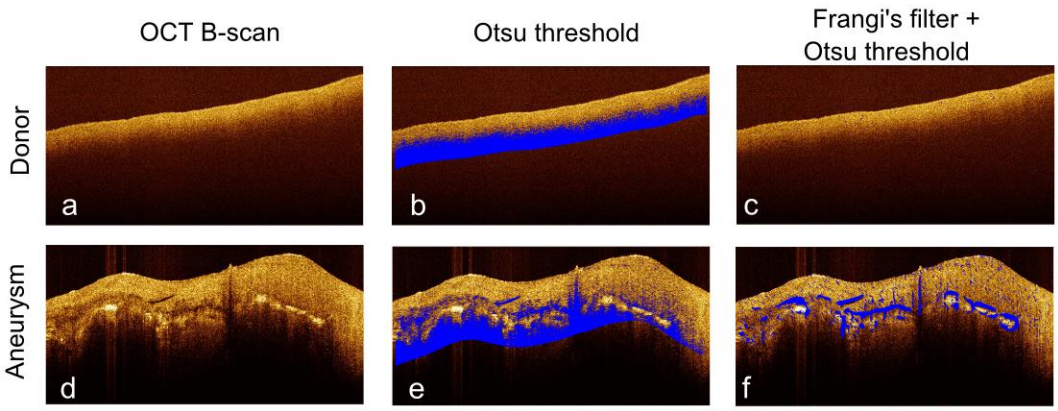

Figure 3. Identification of anomalies in healthy (upper) and pathological (lower) aortas. The proposed multi-scale filter (c, f) provides a better delineation of degradation than a conventional adaptive thresholding (b, e).

The final result needs the parameters σ to be swept, that in this case can be extracted from the size of the expected anomalies. The combination of Frangi's filter and Otsu's method is useful to deal with OCT typical complications during segmentation and thresholding: noise and sensitivity. Noise can be bypassed with big σ, without losing resolution, as happens in typical filtering processes. Sensitivity decay with penetration is not relevant for the intensity histogram, as delineation is computed as a gradient with the Gaussian function second derivatives. Further information about wall status can be obtained from the regions obtained after this thresholding process, such as size and dimension analysis, pattern recognition or others.

4. CONCLUSIONS

The degradation found on aortic samples appears with different spatial dimension depending on the alteration that produces the anomaly. However, these anomalies tend to be horizontally aligned with the inner surface of the vessel, what makes the Frangi's vesselness function a feasible algorithm for the detection of such effects. The response of Frangi's filter is selected through the σ factor of the Gaussian second derivative function. This parameter allows the identification of anomalies according to their dimensions and consequently, to the subjacent alteration. A combination of a Frangi's filter and a posterior Otsu's method provide a fast and reliable identification of reflectivity anomalies, with selective abilities, in a turbid media as the aortic artery.

ACKNOWLEDGEMENTS

This work has been supported by the Spanish Government through the CYCIT projects DA2TOI (FIS2010-19860) and FOS4 (TEC2013-47264-C2-1-R).

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