Automatic IOCT Lumen Segmentation Using Wavelet and Mathematical Morphology

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Abstract

Coronary diseases cause approximately 1 death per minute in USA. Intravascular Optical Coherence Tomography (IOCT) is one of the most used Medical Imaging Modality for coronary investigations. However, segmentation is important to obtain objective information. Hence, better diagnostics and evaluations are provided. Many methods in the literature have not been applied in IOCT segmentation. Therefore, to improve segmentation accuracy, offering more choices to developers, new and alternative approaches are necessary. We present an automatic lumen segmentation approach, based on Wavelet and Mathematical Morphology. The methodology can be summarized as following. First, after preparing the image in a typical preprocessing stage, wavelet is performed to discriminate the tissue from the rest of the image. Next, a moving window Otsu binarization process is carried out. Finally, a Mathematical Morphology takes place to correct, polish and estimate the information previously provided, so that an accurate binary version of the lumen shape, and its contour could be obtained. The evaluation was carried with 130 images from human and pig coronaries, and rabbit's iliac arteries. The high accuracy was demonstrated with values of True Positive (TP(%)) = 99.27±1.29, False Positive (FP(%)) = 3.43±1.51.

1. Introduction

Coronary diseases led to approximately 407,000 deaths in 2007 in United States (USA) [1]. Intravascular Optical Coherence Tomography (IOCT) is one of the references Imaging Modality for coronary investigations. It provides coronary cross-section images with important coronary information. However, objective information; resulting in more reliable diagnostic therapeutic procedure can be obtained with segmentation [2, 3, 4]. The state of the art presents many interesting segmentation methods, using theory of energy minimization process, Wavelets, Otsu, and Fuzzy [2 - 6]. Nonetheless, many of these techniques have not been tested in IOCT, and could be a very interesting solution to IOCT segmentation, improving the current accuracies. Therefore, a method based in wavelet, Otsu, and mathematical morphology, successfully applied in Intravascular Ultrasound (IVUS) [4, 5] was adapted and applied for the purpose herein, creating a novel IOCT lumen segmentation approach.

2. Methodology

The present paper consists of segmenting the lumen of 130 IOCT images, and evaluating the segmentation outcome by computing the parameters of accuracy with the regarding gold standard made by specialists. The images were acquired from 2 patients, 2 pigs, and 1 rabbit, in the Heart Institute of the University of São Paulo Clinic's Hospital, Brazil (InCor), ethics and study protocol were approved and signed, by the regarding committee and patients.

The methodology combines operations in three steps. The **Preprocessing** attenuates the transducer and alignment marks, and convert the image to the polar domain (Figure 1). During **Feature Extraction**, tissue information is extracted by Wavelet and binarized with Otsu [7] (Figure 2). Finally, **Binary Morphological Image Reconstruction** is executed to correct the information previously obtained, and generating a accurate binary version of the lumen, in which the contour is extracted and placed in the original image [4, 5] (Figure 3 and 4).

Preprocessing – In this block (Figure 1), undesirable features for this purpose, such as transducer reflection, and the alignment mark may damage or limit the segmentation accuracy. Therefore, first the catheter is removed by the following equation [4, 5]:

$$I_{NR} = \begin{cases} 0, & if \quad rad < r_{Max} \\ I_{Original}, & otherwise \end{cases}, \tag{1}$$

where $I_{Original}$ is the pixel values of the original image, rad is the radius between the center of the image and the pixel being processed, r_{Max} is the defined maximum radius value from the center to the outermost border of the transducer ring, and I_{NR} is the image without transducer reflection. Next a 2D median filtering is executed, using 5 by 5 window; hence, the alignment marks, and any destructive Speckle effects are attenuated, resulting in

$I_{Filtered}$ (Figure 1(b)). The pre-processing is concluded by converting the image to the polar domain (Figure 1(c)); thus, the 1D appearance simplifies the process [4].

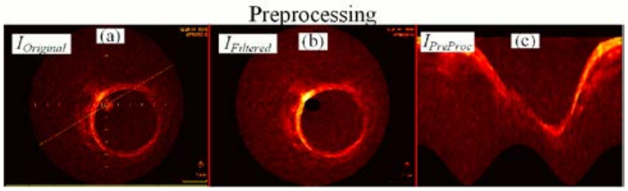

Figure 1. Preprocessing. (a) Original image. (b) Image after catheter attenuation and median filtering ($I_{Filtered}$). (c) Preprocessed image ($I_{PreProc}$), which is the filtered image ($I_{Filtered}$), converted to the polar domain.

Feature Extraction – The Feature Extraction uses operations to identify and distinguish the desired information. Following what was successfully implemented in [4, 5], an association of two operations, Wavelets and Otsu [4, 7], were adopted to acquire tissue information (Figure 2). Hence, one level of Wavelet decomposition using Daubechies 1 (dB1) was carried out, and the $I_{PreProc}$ image was decomposed in four coefficients (Figure 2(a)). The Coefficient of Approximation 1 *cA1* is the one that has most extracted tissue information. (Figure 2(b)). Therefore, *cA1* was the choice to be the tissue information supplier; consequently, lumen region can be recognized. In order to produce an accurately binary lumen object in future steps, the extracted tissue information have to be binarized. Since, the tissue may have angular intensity variations according to the catheter location, a local Otsu binarization process was created, this procedure, binaries the image by using the Otsu thresholding by column. Consequently, for each column, bimodal histogram with tissue and rest of image will be created, and the important information binarized (Figure 2(c)).

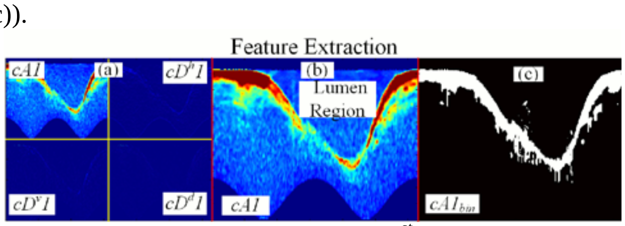

Figure 2. (a) Wavelets coefficients of 1st decomposition. (b) Coefficient of Approximation 1 *cA1*. (b) Coefficient of Approximation 1 *cA1bin*.

Binary Morphological Image Reconstruction – Here, a sequence of mathematical morphology operations [4] was designed to obtain an accurate binary lumen object $lumen_{bin}$ (Figure 3(c)), from $cA1_{bin}$ (Figure 3(a)).

In order to accomplish this task, the operations for the reconstruction are divided in three parts, **Polar Image Reconstruction**, **Opening Detection and Correction**, and **Cartesian Image Reconstruction** (Fig 6). The first, polar image reconstruction, aims to obtain the complete complementary part of the polar lumen object, $l_{polar}*$, (Figure 3(b)). Noise, due to blood features may appear in the lumen location (Figure 3(a)). Since, they may be seen as lumen border information; they can drop the segmentation accuracy. Accordingly, we first completely disconnect them from the main tissue information by filtering the image with a morphological opening procedure.

$$cA1_{binFiltered} = cA1_{bin} \circ S_{circ(3)}, \tag{2}$$

where, $\circ$ is an opening operation, and $S_{circ(3)}$ is a 3 pixel diameter circular structuring element. The structuring element characteristic was chosen to assure that noise could be smoothly disconnected without damaging the information. Once the noise is disconnected from tissue, we first perform a filling procedure, to fill the adventitia region $cA1_{binFilled}$ [4, 8]. Next a region growing area selection is carried out, with the seed placed at the last line and column; hence, removing the disconnected spurious, $selected(cA1_{binFilled})$. Finally, a last closing procedure is performed to smooth possible lumen border irregularities; thus, obtaining complementary polar lumen object, $l_{polar}*$ (Figure 3(b)).

$$I_{polar}* = selected(cA1_{binFilled}) \bullet S_{circ(D)}, \tag{3}$$

where, $\bullet$ is a binary closing, and $S_{circ(D)}$ is a circular structuring element [4] with adaptive diameter, *D* pixels, for *D* being the minimum distance between the catheter center and lumen border (Figure 3(a)).

If the image has branch opening, a detection and correction block is carried out in the *Ipolar**. First, a signal representing the polar image is created. Second, the signal's derivative is calculated, and by finding values higher than a threshold, the opening is detected. Consequently, the correction initiates by removing all values corresponding to the gap, and performing Piecewise cubic Hermite interpolation [4, 5].

Once $l_{polar}*$ (Figure 3(b)) is obtained, with or without opening correction, the lumen object, $lumen_{bin}$, is reconstructed by first carrying out the logic negation of $l_{polar}*$, obtaining the lumen object in the polar domain, I_{polar}, followed by polar to Cartesian conversion, and one last opening operation, for smoothing possible irregularities is performed:

$$lumen_{bin} = I_{Cartesian} \circ S_{circ(Rmin)}, \tag{4}$$

where, $\circ$ is an opening operation and $S_{circ(Rmin)}$ is a circular structuring element with adaptive diameter, R_{min} pixels, where *Rmin* is the minimum radius between the center and border of the lumen [4].

The segmentation is concluded by extracting the lumen contour from $lumen_{bin}$ and placing it on the Original image (Figure 4).

3. Results

The evaluation was performed by segmenting and

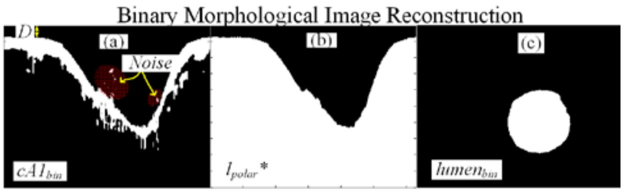

Figure 3. (a) $cA1_{bin}$, the binary tissue information (b) l_{polar} the complementary part of the polar lumen object reconstructed. (c) $lumen_{bin}$, final binary lumen object reconstructed, in the Cartesian Domain.

computing the parameters of accuracy of 130 IOCT images, with gold standards made by experts. Images from, human and pig coronaries, and rabbit's iliac arteries, with different vessel size, and features, such as branch openings and plaques were obtained from the Heart Institute of the University of São Paulo database, Brazil (InCor). They were acquired by an IOCT (LightLab^{TM} Optical Coherence Tomography – LightLab Imaging, Inc., U.K), with pullback of 0.5*mm/s*, and 20*f/s*. Patients have signed a written consent, and the study protocol approved by the local ethic committee. The method was performed in a Desktop computer with an Intel Core 2 Duo 2.53 GHz, 4 GB of RAM, Windows Vista 32 bits and MATLAB (2009a). The computational cost was (5.9 ± 3)*s*, 80*s* faster than manual segmentation, which is 86*s* per image, computed for a related modality, IVUS [8]. The accuracy was obtained by computing the following parameter, True Positive (*TP*), the False Positive (*FP*), the False Negative (*FN*), as well as the Maximum False Positive Deviation (Max_{FP}), the Maximum False Negative Deviation (Max_{FN}) [4]. Figure 4, shows a sample of the segmented images and their accuracy. The good accuracy is proofed in Table 1, in which the *TP*, good result overcame 99% of agreement, and *FP* slightly higher than 3%. The method's precision and robustness can be seen by the small standard deviation of the indexes, a little higher than 1% (Table 1), and the small Max_{FP}, and Max_{FN}, with average smaller than 0.1*mm* in both indexes, for an image size of 6*mm* × 6*mm.* In order to compare the obtained results to others methods, the Overlap Ratio (OR) [2], and Overlap Dice (OD) [3] were also computed, which are close to 96%, and 98%, respectively, in both the results are superior than the mentioned studies.

4. Discussion and conclusion

Despite the efforts made from many groups, methods which could improve accuracy, practicability, and computational cost are still on track. We present an alternative methodology, combining wavelet and mathematical morphology, this methodology was successfully employed in previous studies [4, 5], and now it was adapted and applied for the lumen segmentation in

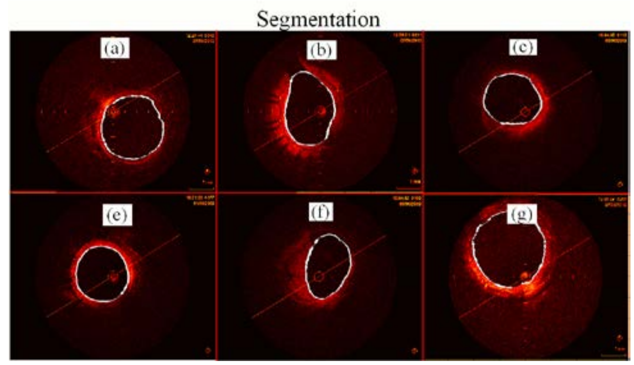

Figure 4. Segmentation outcome.

Table 1. Assessment of accuracy.

T P (%)	F P (%)	F N (%)	MaxFP (mm)	MaxF N (mm)	OR (%)	OD (%)
99.27 ±1.29	3.43 ±1.51	0.72 ±1.26	0.09 ±0.06	0.06 ±0.07	95.99 ±1.78	97.95 ±0.94

IOCT images. The methodology was based on four stages. The first, **Preprocessing** block, the image is prepared, normalization and filtering are carry out. The second, **Feature Extraction**, tissue information are obtained by Wavelet and Otsu [7]. Next, **Binary Morphological Image Reconstruction** is performed; hence, information are corrected and the binary lumen object constructed. Finally, the segmentation is concluded by extracting from the object and placing the contour in the original image.

The methods accuracy, precision, and robustness were assessed and corroborated by computing the regarding parameters from a challenge set of images (Table 1). The obtained outcomes rendered higher efficacy than results from recent works in the literature [2, 3]. We understand that a complete conclusion among methods can only be made using the same database, and computer. Nonetheless, it is also important to compare some indices. In [2] a lumen segmentation approach was presented and an OR near 94% was obtained, value near 3% below what was obtained in this work. In the paper presented by [3] an appreciable value of OD close to 97%, was obtained, yet it is still below than the 97.95% of this approach. In addition, the proposed method is completely automatic, and also composed by simpler and lighter operations, in which the use of heavy computational tasks, related to energy minimization procedures, were prevented.

The approach efficiency, computational cost and practicability, motivating the use and evolution of the method. Therefore, an alternative and reliable lumen segmentation method for IOCT images is available. The major contributions are: (a) A wavelet associated with an alternative version of Otsu for a tissue information extraction, and; (b) a new sequence of morphological operations, designed to reconstruct lumen object, resulting in an accurate segmentation. Finally, in addition to modify parameters to improve efficiency, future works will also investigate ways to segment the stent structure; hence, by having the lumen and stent segmented, the neo-intima re-stenosis can be objectively and automatically quantified.

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