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3D Reconstruction of Coronary Arteries using Frequency Domain Optical Coherence Tomography Images and Biplane Angiography

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Abstract— **The aim of this study is to describe a new method for three-dimensional (3D) reconstruction of coronary arteries using Frequency Domain Optical Coherence Tomography (FD-OCT) images. The rationale is to fuse the information about the curvature of the artery, derived from biplane angiographies, with the information regarding the lumen wall, which is produced from the FD-OCT examination. The method is based on a three step approach. In the first step the lumen borders in FD-OCT images are detected. In the second step a 3D curve is produced using the center line of the vessel from the two biplane projections. Finally in the third step the detected lumen borders are placed perpendicularly onto the path based on the centroid of each lumen border. The result is a 3D reconstructed artery produced by all the lumen borders of the FD-OCT pullback representing the 3D arterial geometry of the vessel.**

I. INTRODUCTION

Accurate assessment of vessel morphology is indispensable for diagnosing and treating coronary artery disease [1], [2]. Coronary angiography is the conventional method for assessing the morphology of the arteries [3] as it produces two-dimensional (2D) images that depicts the arterial lumen. Although coronary angiography is widely used by the physicians, it gives unreliable or no information, regarding the structure of the arterial wall (eg. thickness and plaque burden) and the plaque rupture probability [4].

To overcome these limitations the precise 3D arterial geometry representation is needed. The most common methods used for the 3D reconstruction of coronary arteries are using Intravascular Ultrasound (IVUS) and angiographies. Angiography images allow the extraction of the artery path. However, no information on the interior of the artery can be derived from these images. On the other hand, IVUS images provide information about the interior of the coronary arteries failing to provide information though, on the orientation of the arteries in the 3D space. The fusion of data of the two imaging techniques is of utmost importance in order to obtain accurate 3D reconstructions of coronary arteries.

Several semi-automated methods for 3D arterial reconstruction have been proposed during the past years [5]-[7]. The methods processed IVUS and angiography images and the reconstruction was based on the path of the catheter. Traditionally in an IVUS reconstruction method we use the 3-D catheter path (extracted from two orthogonal angiographies), and the lumen borders of the IVUS frames that correspond to the R-peak of the ECG signal (due to the catheter movement inside the vessel). The catheter in each R-peak frame (which is in the center of the image) is used for guiding the vector that places the lumen borders in the 3-D path (Fig. 1 (b)).

Two-dimensional Frequency Domain Optical Coherence Tomography (FD-OCT) is becoming the method of choice in accessing vessel and plaque morphology, since it produces high resolution tomographic images of the internal vessels microstructure [8]. In contrary to IVUS, the resolution of FD-OCT is higher [9], [10], thus the plaque morphology and the lumen borders can be more accurately detected. Consequently the 3D arterial geometry of a reconstructed artery using the FD-OCT lumen borders would be more reliable than using the IVUS lumen borders. Since FD-OCT speed is up to 25 mm per second (to limit procedure time) the frames that correspond to the R-peak of the ECG signal are less than 8 in an FD-OCT pullback (Fig. 1 (c)). The small number of R-peak frames along with the catheter movement inside the vessel makes the 3D FD-OCT reconstruction using the traditional reconstruction methods (that are based on the catheters path) not possible (Fig. 1).

In the present work we present a new semi-automated 3D reconstruction method using FD-OCT images and biplane angiographies. The proposed method overcomes the limitation of the catheter path and instead uses the center line of the vessel from the two biplane projections. The result is a 3D reconstructed artery produced by all the lumen borders of the pullback which represent the 3D arterial geometry of the vessel.

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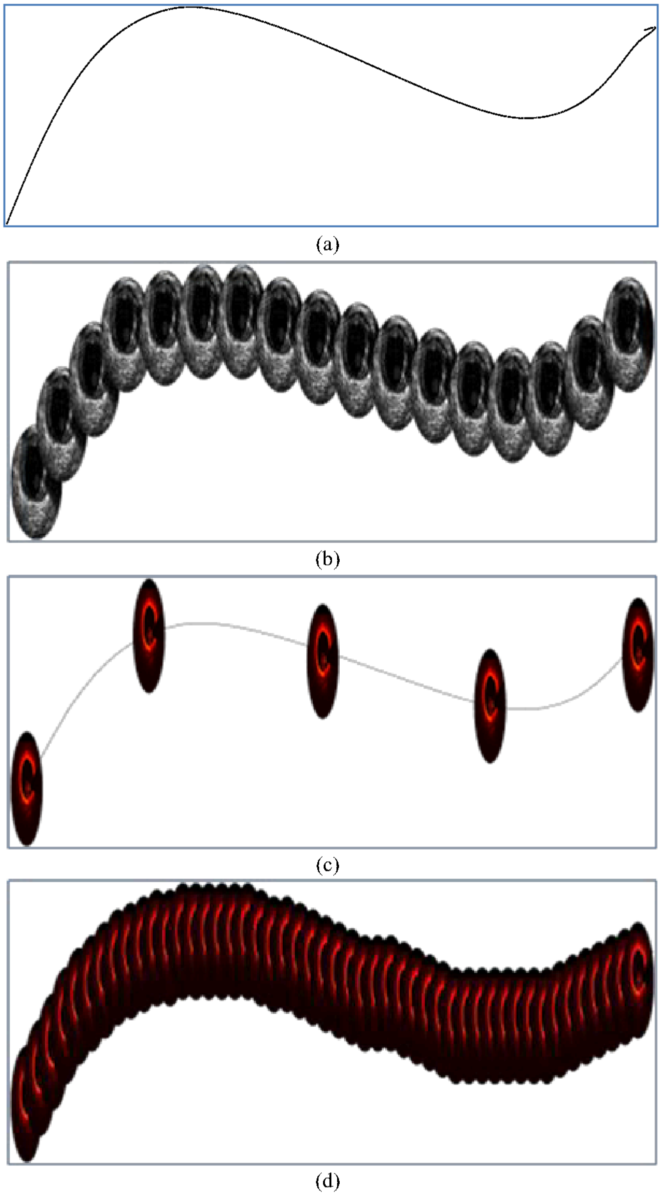


Fig. 1: 2D schematic presentation of the frames position on the 3D path : (a) the path of the catheter, (b) IVUS frames that correspond to R-peak placed on the catheter path, (c) FD-OCT frames that correspond to R-peak placed on the catheter path and (d) FD-OCT frames placed on the catheter path.

II. Materials And Methods

The proposed 3D reconstruction method is based on a three step approach:

A. The lumen borders are automatically detected.
B. The center line of the vessel from the two biplane projections is semi-automatically detected.
C. The detected lumen borders are placed perpendicularly onto the path using the centroid of each lumen border.

A. Lumen border detection

The FD-OCT equipment acquires individual A-lines containing the information of the reflected optical energy as a function of time. These individual A-lines are stored sequentially in a 2-D matrix (I_{Matrix}) with each line corresponding to polar intensity data $I(r,\theta)$, with r representing the range dimension and θ the acquisition angle. Each frame corresponds to a $I(r,\theta)$. In order the true morphology of the tissue to be revealed, the polar 2-D data ($I(r,\theta)$) must be converted to Cartesian coordinates.

To find the lumen border we process each polar image (I_{Matrix}). The procedure consists of the following steps:

i. apply a Gaussian filter on the initial image I_{Matrix},
ii. perform automatic thresholding [11] method in order different binary objects to be revealed,
iii. erase the non-zero objects with length less than $\frac{1}{length(I_{Matrix})}$ and mean intensity greater than 200. These objects corresponds to artifacts (catheter artifact etc),
iv. scan each column of the image from top to bottom and save the first non-zero pixel of the column in order to find the lumen contour and
v. transform the image I_{Matrix} from cartesian to polar coordinates ($I(i,j)$) in order the true morphology of the tissue to be revealed.

The polar coordinates r and θ are converted to the Cartesian coordinates i and j, by using the trigonometric functions sine and cosine: $i = r\cos\theta$, $j = r\sin\theta$. A schematic presentation of the procedure followed is shown in Fig. 2.

B. Center line extraction

In order the 3D path to be calculated the center line from the two biplane projections must be computed. The procedure followed was to mark manually the silhouette of the vessel from start to end of the pullback and compute the center line of the silhouette in each biplane projection. To compute the center line, the perpendicular distances from one border to the other are computed. In each perpendicular distance the middle point is selected as a center line point. By connecting the middle points the center line is computed.

For a biplane projection $Bl(i,j)$, let Lb_1 and Lb_2 be the two silhouette borders and $D(i,j)_{1,2}$ the perpendicular distance from a pixel $p_1 \in Lb_1$ to a pixel $p_2 \in Lb_2$, where $i,j \in Bl(i,j)$. The center line of the two silhouette borders is defined as:

$$CL = \sum_{k=1}^{l} \frac{D_k(i,j)_{1,2}}{2}, \qquad (1)$$

where l is the length of Lb_1. A schematic presentation of the center line path computation using the perpendicular distance from one border to the other is shown in Fig. 3.

Using the method by Bourantas *et al* [5] for 3D reconstruction in IVUS, the 3D path is computed. The method was modified in order the 3D path to be computed using the center line path and not the catheter path in the two biplane projections. Additionally the lumen borders from all OCT frames are used instead of using only the lumen borders from the IVUS frames that correspond to the R-peak.

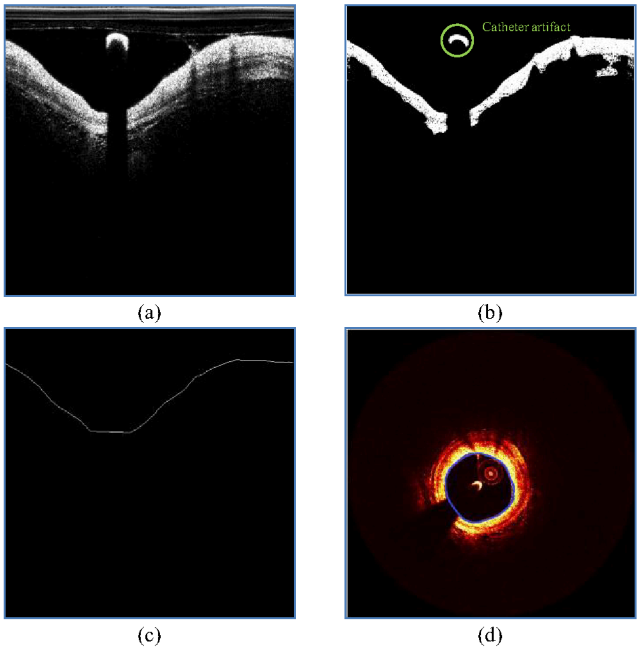


Fig. 2: Schematic presentation of the procedure followed to detect the lumen border: (a) the initial image, (b) the image after applying the automatic thresholding method and the catheter artifact marked with green, (c) the lumen border detected after scanning the image from top to bottom and (d) the OCT image with the detected lumen border marked with blue.

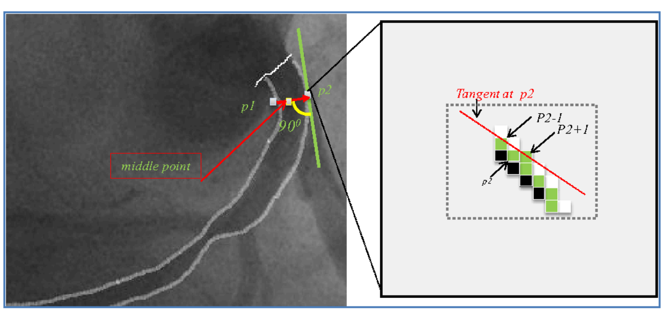


Fig. 3: Schematic presentation of center line path computation using the perpendicular distance from one border to other.

C. Placement of the OCT lumen borders onto the 3D path

The vessel center line is divided in equidistant segments corresponding to the number of FD-OCT frames. In order the lumen borders to be placed perpendicularly to the 3D path, the centroid of each lumen border area is computed.

The centroid $CN(C_x, C_y)$ of each lumen border for n pixels of the border is defined as:

$$C_x = \frac{1}{6A}\sum_{q=1}^{n-1}(x_q + x_{q+1})(x_q y_{q+1} - x_{q+1} y_q), \quad (2)$$

$$C_y = \frac{1}{6A}\sum_{q=1}^{n-1}(y_q + y_{q+1})(x_q y_{q+1} - x_{q+1} y_q), \quad (3)$$

where A is the lumen area defined as:

$$A = \frac{1}{2}\sum_{q=1}^{n-1}(x_q y_{q+1} - x_{q+1} y_q). \quad (4)$$

Their relative axial twist is extracted using the sequential triangulation algorithm. Finally, the absolute orientation of the first OCT frame is estimated using the side branches of the artery which can be identified in both the angiographic and the FD-OCT images.

Thus one set of point cloud is created from the previously described steps. The set is imported into a visualization module [12], where a surface is constructed corresponding to the silhouette of the lumen.

III. Results

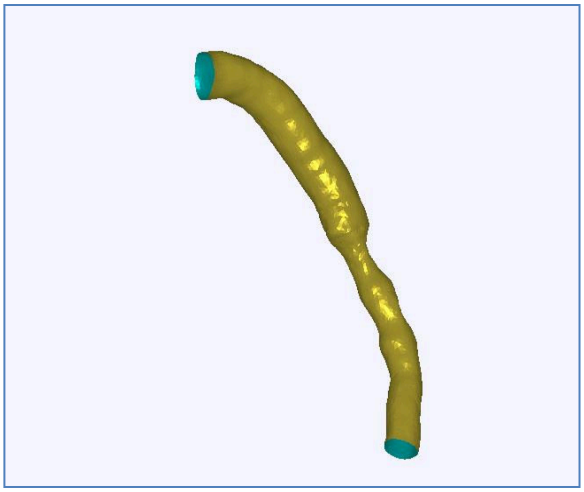
The 3D reconstructed artery was produced using an OCT pullback provided by the San Giovanni Hospital of Rome. The pullback was acquired using an FD - OCT OCT equipment (LightLab Imaging, Inc). The graphic result of the proposed 3D reconstruction method is shown in Fig. 4 (a). As shown in Fig. 4 (b) a stenosis is detected in the biplane projection. The same stenosis is detected in the reconstructed vessel as shown in Fig. 4 (c), where the reconstructed lumen is back projected on the silhouette of the angiographic image. Additionally, Fig. 4 (c) shows that the projection of the 3D reconstructed vessel correspond well to the entire vessel's silhouette in the angiographic images.

IV. Discussion

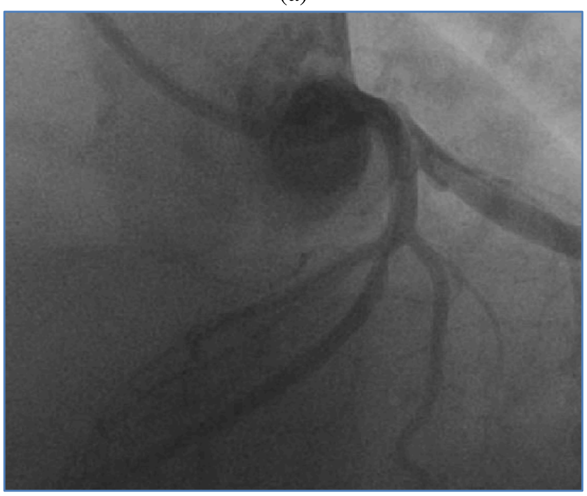
In this work, we present a new semi-automated method for 3D reconstruction of the coronary arteries using FD-OCT images and biplane angiographies. The method is based on the fusion of data obtained by biplane angiography and FD-OCT and uses a segmentation algorithm for detecting the lumen wall in FD-OCT images. The method overcomes previously mentioned limitations regarding the extraction of the catheter path and the R-peak frames in FD-OCT images.

Instead of using the catheter path, for the first time the center line of the vessel from the two biplane projections is used in order the 3D path to be constructed. The centroid of the lumen areas is used to guide the vector that places the lumen borders onto the 3D path. The result is a 3D reconstructed artery produced by all the lumen borders of an FD-OCT pullback. The 3D reconstructed artery represents the 3D arterial geometry of the vessel.

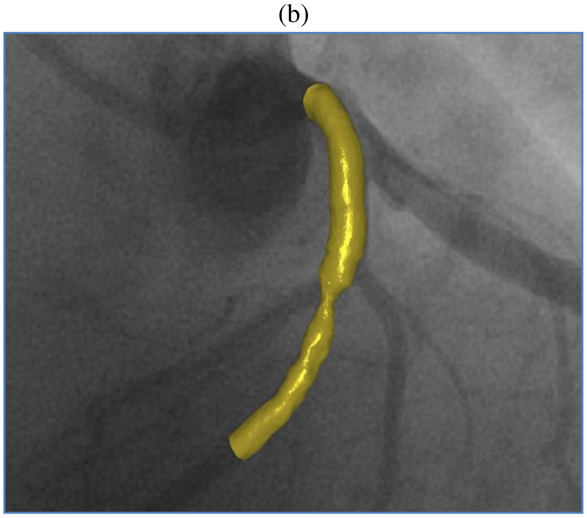
In order the proposed method to be fully validated FD-OCT and IVUS examinations from the same vessel segment of a specific patient must be performed. Two 3D reconstructed arteries must be produced: the one using the IVUS pullback and the traditional reconstruction method [5] and the other using the FD-OCT pullback and the proposed method. The two 3D models will represent the 3D arterial geometry of the same vessel and the models will be fully comparative.



(a)



(b)



(c)

Fig. 4: OCT reconstructed artery: (a) the reconstructed artery that represent the 3D arterial geometry of the vessel, (b) the one of the two biplane projection used to extract the 3D path and (c) the back projection of the reconstructed artery on the biplane projection.

V. Conclusions

The proposed method for the 3D reconstruction of coronary arteries was based on the fusion of biplane angiographic and FD-OCT images. The method used an algorithm for the identification of the lumen borders in FD-OCT images and a new method for extracting the 3D path and guiding the lumen borders to the path.

The back projection of the reconstructed artery on the biplane projection indicate that the method is accurate and can be applied in clinical settings providing further information on vessel morphology and atheromatosis.

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