Reconstruction of stented coronary arteries for CFD analyses: from *in vitro* to patient-specific models

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***Abstract*— This study describes a method for the reconstruction patient-specific stented coronary artery models from medical images routinely acquired during percutaneous coronary intervention. The resultant high fidelity geometries allow evaluating local hemodynamic alterations within coronary arteries after the stent deployment. The method was developed and validated on a phantom resembling a typical human coronary artery. Subsequently, it was applied to an *in vivo* OCT dataset to demonstrate its applicability to patient-specific cases.**

***Keywords*— Optical coherence tomography, image segmentation, computational fluid dynamics, coronary stent.**

I. Introduction

VASCULAR tissue response to percutaneous coronary intervention, such as in-stent restenosis, is influenced by alterations of local blood flow pattern due to stent implantation [1]. Computational fluid dynamics (CFD) simulations allow the evaluation of hemodynamic variables that are known to trigger in-stent restenosis but cannot be measured *in vivo*.

Medical image processing is a central step for creating accurate patient-specific vessel models to be used for CFD studies. Coronary artery imaging is largely performed both during diagnostic phase and mini-invasive treatment. Among the available intravascular imaging modalities, optical coherence tomography (OCT) ensures the highest resolution (axial resolution of 12-15 μm and lateral resolution of 20-40 μm) [2]. The main drawback of OCT is that the correct orientation of the vessel in the space is not captured [2]. Consequently, information from different imaging techniques, such as angiography, is needed to reconstruct the 3D vessel geometries.

In the present work, we propose a reconstruction method based on OCT and angiographic images for creating patient-specific stented coronary artery models for the execution of CFD analyses. The reconstruction method was developed and validated on a phantom, which is representative of a typical human coronary artery. Subsequently, the method was applied to an *in vivo* image dataset to demonstrate its applicability to patient-specific cases.

II. Material and Methods

A. OCT-based reconstruction method

The workflow for the reconstruction of stented coronary artery models from OCT and angiographic images is depicted in Fig. 1. Briefly, an automatic segmentation method is used to detect the lumen contours and stent struts in each OCT frame. Details about this segmentation method are reported elsewhere [2]. The 3D shape of the treated artery is provided by the vessel centreline, which is reconstructed from two angiography projections using the software CAAS (Pie Medical Imaging BV, The Netherlands). The 3D centerline is used to properly arrange the lumen contours and stent struts, so that the twist angle error is reduced. The 3D model of the coronary artery with the stent is obtained from the aligned components and is used to perform the CFD analysis.

B. Validation of the reconstruction method

A phantom of a coronary vessel resembling a human left anterior descending coronary segment with bifurcations was 3D printed (Fig. 2). After the deployment of a Multi-Link 8 stent (Abbott Vascular, USA) by an interventional cardiologist, an OCT acquisition was performed. The phantom was also scanned with an X-ray micro computed tomography (μCT) system and the obtained slices were processed to extract the vessel and stent centerlines. Then, the OCT-based reconstruction method was employed to obtain the 3D model of the vessel phantom.

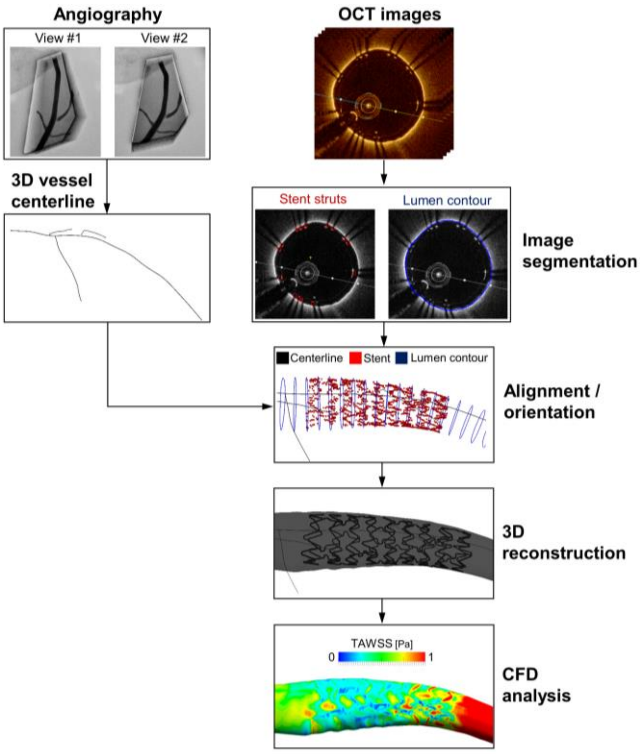

Figure 1 – Workflow for 3D reconstruction of stented coronary artery CFD models from angiography and OCT.

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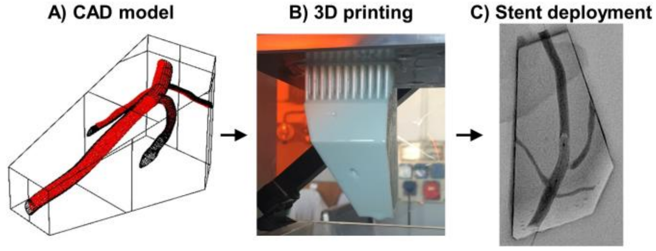

Figure 2 – Coronary artery phantom: A) CAD model of a coronary vessel resembling a patient-specific left anterior descending coronary artery with bifurcations. B) 3D print of the phantom. C) Angiography after stent deployment.

The automatic segmentation algorithm of the OCT images was validated against manual segmentation, executed by two independent image readers. Statistical correlation, agreement, and linear regression between datasets were tested. Differences between the automatic and manual segmentation methods were evaluated by computing similarity indexes.

The 3D reconstruction was compared against that obtained from µCT, which was considered as reference.

C. Application to a patient-specific case

The reconstruction method was applied to OCT and angiographic images of the right coronary artery of a patient treated at the Institute of Cardiology, Catholic University of the Sacred Heart (Rome, Italy) with a 3.5x28 mm Xience Prime stent (Abbott Vascular).

The obtained 3D stented model, which includes one bifurcation, was discretized using 5,957,992 tetrahedral elements. A transient CFD analysis was performed using Fluent (Ansys Inc.). A typical right coronary artery flow waveform [3] was applied at the inlet with a flat velocity profile. The mean flow-rate was estimated by counting in the angiographic projections the number of frames required for the contrast agent to pass from the inlet to the outlets [4]. A flow-split 0.94:0.06 for the distal main branch and side branch, respectively, was applied at the outlets. Simulations settings are reported in [5].

III. Results

A. Validation of the reconstruction method

High linear correlation was found between the automatic and manual segmentations in terms of lumen area values ($r=0.999$, $p<0.005$). The values of similarity indexes confirmed the correct identification of lumen contours (i.e. values of evaluated indexes > 96%) and a good detection of the stent (i.e. values of evaluated indexes > 77%).

The 3D model reconstructed from OCT showed good consistency with acquired images. The regions with malapposed stent struts within the 3D model were consistent with those in the OCT images. The percent difference in area and relative error of volume between the OCT and µCT lumen reconstructions were 17.5% and 7.1%, respectively. The median of the total distances between stent reconstructions was 198.75 µm.

B. Patient-specific case

The local hemodynamics of the patient-specific case was analyzed in terms of wall shear stress (WSS) descriptors. Figure 3 shows the WSS distribution along the lumen surface. The region exposed to time-averaged WSS lower than 0.4 Pa, which is related to the risk of restenosis, was confined to the stent region with a percentage area of 39.5%.

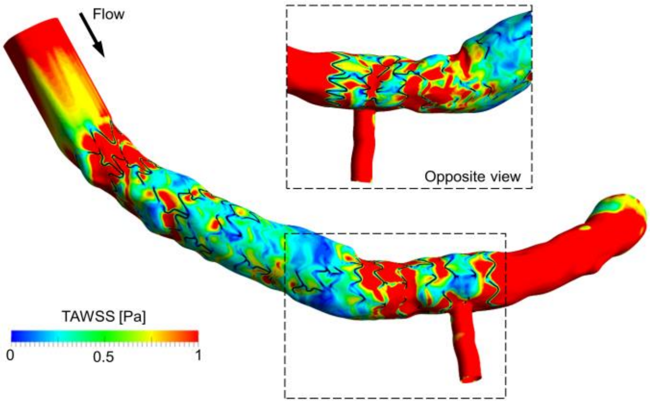

Figure 3 – Contour map of time-averaged WSS (TAWSS) along the lumen of the right coronary artery segment of a patient treated with a 3.5x28 mm Xience Prime stent.

IV. Conclusion

This study describes a validated method for the reconstruction of patient-specific stented coronary artery models from medical images routinely acquired during percutaneous coronary intervention. The resultant high fidelity geometries allow evaluating local hemodynamic alterations within coronary arteries after stent deployment, with outcomes that are peculiar of each clinical case.

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