Patient-specific virtual simulations of stenting procedures in coronary bifurcations

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Abstract – Currently, most of the numerical models that simulate stenting procedures lack of patient-specificity resulting in their limited use in the clinical field. Indeed, simulating stenting procedures in idealized geometries can only provide standard guidelines. On the other hand, patient-specific tools able to realistically simulate different interventional options might facilitate clinical choices and increase their current application.

Thus, the aim of this work is the implementation of a patient specific virtual model that uses image-based reconstructions of coronary bifurcations. Two cases of adult males treated with a provisional T-stenting without final kissing balloon were investigated.

Keywords - Numerical modelling; Stent; Coronary bifurcations; Image-based reconstructions.

I. Introduction

Recently, several numerical models have been implemented to provide new information on stenting procedures in coronary bifurcations and overcome their main clinical issues [1,2]. The majority of these models simulates stenting procedures in idealized geometries, lacking patient-specificity. Accordingly, these models can only provide standard guidelines and not specific indications optimal for the planning of each patient treatment.

Hence, the aim of this work is to implement a patient-specific virtual model that uses image-based reconstructions of atherosclerotic bifurcations. Attention is paid to the insertion of the stents on the catheter and their correct positioning in complex geometries. In particular, two cases of adult males treated with a provisional T-stenting without final kissing balloon are investigated (case A and B). Further developments involve the validation of the final geometrical configurations obtained via finite element models with image-based reconstruction of post-stenting geometries and the creation of fluid volume for the fluid dynamic numerical simulations.

II. Materials And Methods

A. Coronary Bifurcation Models

The pre-stenting geometries are generated from conventional coronary angiography (CCA) and computed tomography angiography (CTA) [3] and are used to construct 3D solid models of the coronary bifurcations investigated (Fig. 1). First, the open-source software package VMTK [4] is used to indentify the vessel centerline. Second, external wall surfaces were created with circumferential cross sections perpendicular to the centerlines using the CAD software Rhinoceros 4.0 Evaluation (McNeel & Associates, Indianapolis, IN, USA). The diameters of the external wall are chosen in order to respect the internal diameter and wall thickness of the arterial branches investigated in a physiological healthy state [5]. External wall diameters varied from a maximum of 5.2 mm at the inlet till 1.6 mm at the outlet of the second bifurcation of case A. The geometry is discretized using Ansys ICEM CFD (ANSYS Inc., Canonsburg, PA, USA) with a hexahedral mesh (Fig. 2a).

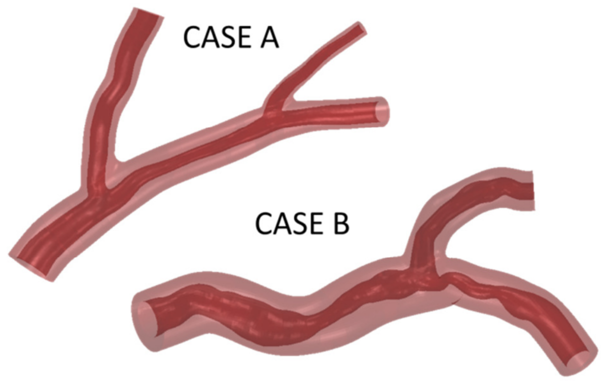

Figure 1. 3D models of atherosclerotic coronary bifurcations. Two cases of the pre-stenting geometries of the internal surface proposed in Cardenes et al. [3] are used (A and B). Vessel diameters and wall thicknesses respect the physiological values of LAD and its first diagonal branches.

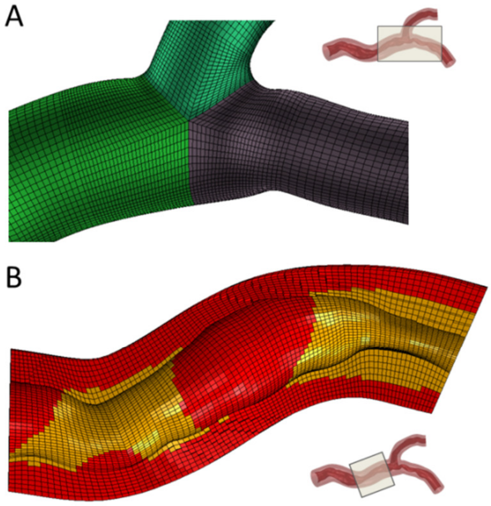

Figure 2. A) Example of hexahedral discretization of Case B. B) Identification of atherosclerotic plaques based on the distance of vessel nodes from the external wall centerline.

Finally, atherosclerotic plaques were identified based on the distance between each node and the centerline of the external wall surface (Fig. 2b). This identification was only been hypothesized since non imaging data was available.

The material properties used for the arterial wall and the plaques replicate the mechanical behavior in the circumferential direction of the media layer and cellular plaques, respectively. The hyperelastic constitutive models implemented are described in details in Gastaldi et al. 2010 [2].

B. Stent and Balloon Angioplasty Models

Stent geometries are obtained using the previously mentioned CAD software and resemble the Endeavor Resolute (Medtronic, USA) and the Multilink Vision (Abbott Lab., USA) stents. Their material, a cobalt-chromium alloy, is described through a Von Mises-Hill plasticity model [6]. Polymeric angioplasty balloon models respect those previously described in Morlacchi et al. [6].

C. Preliminary simulations: crimping and bending

To precisely position the devices in the complex patient-specific geometries, preliminary simulations of crimping and bending of the devices are performed using the finite element commercial code Abaqus/Standard (Dassault Systemes, USA). In the bending simulation, displacement conditions are applied to the links of the device which is in contact to an internal cylinder following the vessel centerline. A soft contact with linear pressure-over closure relationship is used.

D. Final simulations

Numerical simulations of stents deployment are performed using the ABAQUS/Explicit modeling commercial code, as a quasi-static process [6]. The two clinical cases are virtually performed both involving the left anterior descending artery (LAD). The following procedural indications were provided by the hospital Doctor Peset in Valencia (Spain) where the treatments were actually performed:

- Case A: two Endeavor stents were implanted across the two bifurcations between the LAD and the first and second diagonal branches. After a pre-dilatation with a 15 mm long angioplasty balloon with a diameter of 2.5 mm, the distal device was inserted and expanded at 12 atm with a 2.75 mm balloon. Afterwards, the proximal stent was implanted across the first bifurcation with a 3 mm angioplasty balloon inflated at 14 atm resulting in a small overlap with the previously implanted device.

- Case B: a Multilink Vision stent with nominal diameter and length of 3 mm and 28 mm was deployed at 14 atm across the bifurcation between the LAD and the first diagonal branch. Procedure was ended with a post-dilatation at 18 atm in the proximal part of the main branch using a 3 mm non-compliant balloon.

III. Results And Discussion

A. Bending procedures

Figure 3 shows the positioning of the Multilink stent following the centerline of the artery of case B obtained after vessel pre-dilatation with a 2.00 mm angioplasty balloon.

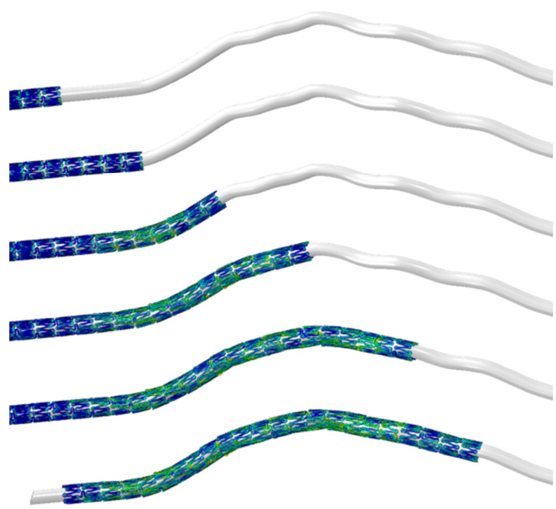

Figure 3. Simulation of stent advancement on a guide that follows the centerline of the main vessel of Case B. Contour maps represent the Von Mises stresses on the device.

B. Virtual clinical cases

In figure 4, the virtual implantation of the device in case A is depicted. Ideal opening of the vessel and straightening due to insertion of rigid stents are evident. Figure 5 shows the stress state on the devices and the arterial wall at the end of the recoil. Peaks of stresses and deformation are obtained in the overlapping region highlighting criticism of the area.

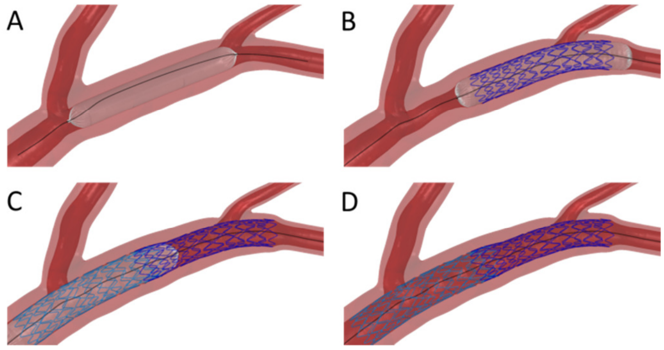

Figure 4. Simulation of the clinical procedure performed in Case A: A) vessel pre-dilatation with a 2.5 mm angioplasty balloon; B) deployment of a 2.75 mm Endeavor stent across the distal bifurcation; C) expansion of a second 3.00 mm Endeavor stent across the proximal bifurcation; D) configuration after the elastic recoil.

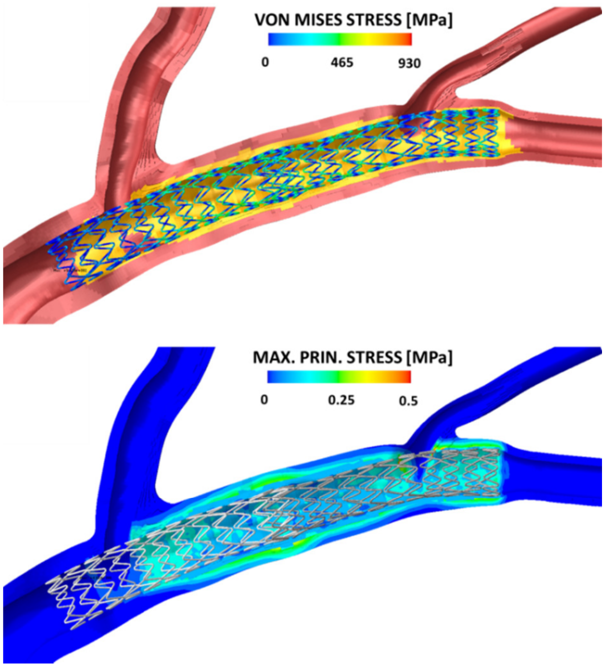

Figure 5. Contour maps of Von Mises stresses on the stents (top) and of maximum principal stresses in the arterial wall (bottom) for case A.

C. Further developments

Post-stenting geometries (Fig. 6) are being used to provide image-based validation of these numerical models [3]. Final geometrical configurations will be used for patient-specific CFD simulation [7].

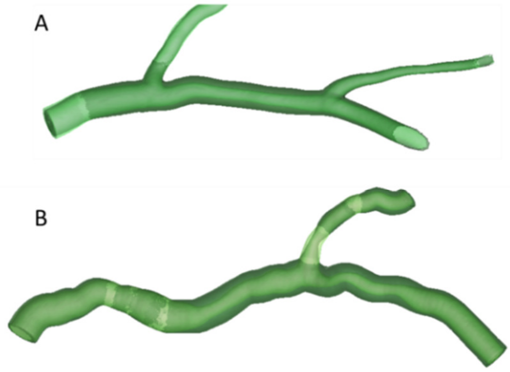

Figure 6. Comparison of image-based reconstructions of pre- and post-stenting geometries for case A and case B [3].

IV. Conclusions

This work shows the feasibility of implementing a patient-specific virtual model replicating actual clinical cases. Standard medical images (CCA and CT) were used to create the 3D pre-stenting geometry and the intervention was simulated following the clinical indications provided. Moreover, simulations of crimping and insertion were necessary to find the correct positioning of the devices in complex image-based geometries.

Acknowledgments

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