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► **To cite this version:**

Bernard Al-Helou, Catherine Dupont, Aline Bel-Brunon, Wenfeng Ye, Adrien Kaladji, et al.. Towards a patient-specific simulation of the balloon angioplasty treatment technique. *Surgetica* 2019, Jun 2019, Rennes, France. hal-02525801

HAL Id: hal-02525801

<https://hal.science/hal-02525801>

Submitted on 2 Apr 2020

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Towards a patient-specific simulation of the balloon angioplasty treatment technique

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This work addresses the issue of patient specific (PS) simulation of balloon angioplasty (BA). As a further step towards an ideal BA simulation scenario, this study focuses on two main issues: material modeling using plastic constitutive law to imitate the plaque permanent deformation and segmentation of the CT images to extract PS 3D geometry of the stenosed artery.

1 Introduction

Percutaneous Transluminal Angioplasty (PTA) is a minimally invasive treatment which consists of inserting and inflating a balloon in a stenosed artery aiming to restore its original lumen. Stents are usually used to maintain the arterial lumen reached by PTA; however, their use is questioned due to restenosis issues. Therefore, the issue of anticipating treatment outcome, in particular residual deformations after PTA remains open.

Several studies have developed computational models for PTA, mainly using finite elements methods (FEM) [1], either towards balloon design or treatment planning. Some FE studies related to the atherosclerotic plaque have considered 2D plaques biomechanical responses under different loadings [2,3] but it has been shown that plaque behavior is more accurately simulated with 3D models [4,5]. Few other studies considered 3D stress distributions within the plaques to analyze their sensitivity to geometrical and material composition changes [6-11].

Most studies modeled the plaque using an isotropic or anisotropic hyper-elastic constitutive law. A recent study shows that considering permanent deformations (using plastic model) should further be investigated in the aim of planning a PTA with FE simulations [12]. In addition to the constitutive law,

one other main issue influencing PTA outcomes is the PS material properties assigned to the plaque. It is a challenge to experimentally characterize the plaque behavior *in-vivo*. The alternative is to deduce this mechanical behavior from the PS pre-operative images [1], as idealized geometries studies demonstrated that mechanical stresses are sensitive to small changes in plaque geometry and material properties [10,13].

Several imaging methods exist to model PS geometries of stenosed arteries such as histology, magnetic resonance imaging (MRI), computed tomography (CT) and intravascular ultrasounds (IVUS). Yet they all have limitations [1]: histology and high-resolution MRI can provide detailed description of the plaque but cannot be carried out *in vivo* [2,10]. Clinically used MRI can furnish detailed 3D description of soft plaques (though less spatially resolved) *in vivo* [3] but most protocols do not include it [14]. IVUS allows for 3D reconstruction of the *in vivo* artery, but presents risks on patients' safety and does not help differentiating plaque components. Finally CT technique can provide a 3D representation of stenosed vessel *in vivo*, especially by its ability in identifying calcifications, but with incapacities in distinguishing between other components such as fibrous and lipid-rich plaques. Up to our knowledge, studies that used CT as input images for geometrical PS BA simulations only extracted the stenosed lumen [11]. As CT is the only imaging technique used in BA protocols, we chose to focus on this acquisition method to build our PTA model. A complete workflow for PS simulation of PTA from CT images is under development. Here we focus on two essential steps of this workflow: 1. simulating residual deformations in the plaque after PTA using a plastic model; 2. extracting PS plaque composition and geometry from CT images using a segmentation approach.

2 Material and Methods

2.1 FE simulation

The workflow for a general FE simulation of PTA in an idealized stenosed arterial geometry has been studied. A cylindrical artery of 30 mm in length [8], 1 mm in thickness and stenosed by a non-symmetric calcified plaque of 60 % at its center was modeled as seen in Fig. 1a. Both the artery and the plaque were meshed using tetrahedral elements with connected meshes between the two parts (Fig. 1a). The artery at its two extremities was fixed in both translational and rotational motions. The Neo-Hookean hyper-elastic model was used for the arterial material with parameters from [15]. An isotropic bi-linear plastic model was considered for the calcified plaque. Young modulus for this plaque type was obtained from [16]. A displacement driven cylindrical balloon, mimicking the behavior of a non-compliant stiff balloon was modeled inside the stenosed artery. The 15 mm in length balloon (of shell elements) was inflated until reaching the healthy arterial wall and then deflated progressively. This non-linear numerical analysis including large deformations and contacts was solved using ANSYS implicit solver.

2.2 Patient-specific plaque geometry segmentation

CT angiography images of a highly calcified abdominal aortic stenosis were processed using 3D slicer and ITK-snap software. After selecting the desired region of interest and removing secondary branches, the lumen was extracted using the active contour method. Then the calcified plaque was segmented based on its high density. A subtract Boolean operation was then performed obtaining the un-calcified (lipid) plaque from what remains after removing the segmented lumen and calcified parts. Finally a growing operation was applied to the regions segmented previously in order to create the arterial wall (which cannot be clearly seen from the CT images).

3 Results

Fig. 1 shows the stenosed arterial behavior during and after BA treatment technique simulated in idealized geometry. Radial lumen gain is achieved along the plaque length after balloon deflation (Fig. 1c). In addition permanent longitudinal deformation

is observed highlighting the importance of considering the 3D analysis in such studies.

In order to consider later a PS geometry in the simulation, CT scans are segmented as presented in Figs. 2 (a and b). Fig. 2 shows a coronal cross section of the CT scans. The 3D geometry is then generated from the segmentation label-map after some smoothing iterations (Fig. 2c).

By mapping material properties based on CT densities, this geometric model could be used to attain a complete PTA simulation workflow.

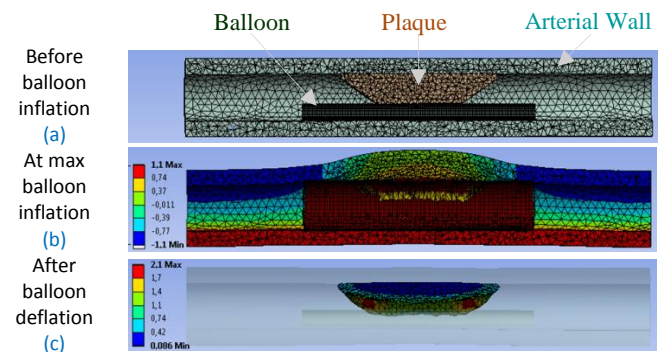


Fig 1: Stenosed artery behavior before, during (radial deformations in mm) & after (Equiv. plastic strains) BA.

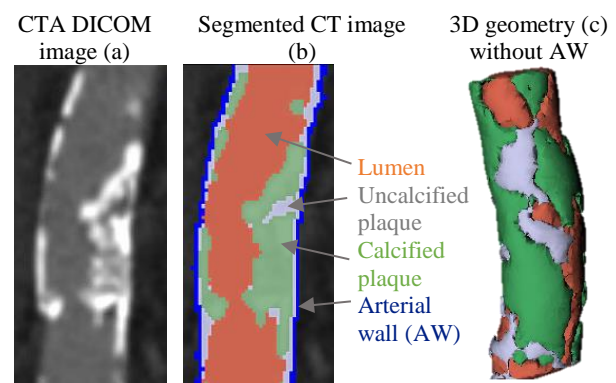


Fig. 2: From CT scans to 3D model of stenosed artery with highly calcified plaque. Lumen is labeled in orange, calcified plaque in green, un-calcified plaque in grey and arterial wall (AW) in blue.

4 Conclusion

This study describes the first steps towards a PS simulation of BA treatment: PS geometry segmentation of different plaque components and FE computation of residual deformations in a generic stenosed artery. After combining both, evaluation of plastic material model contribution in mimicking plaque behaviors will be performed using post-operative CT-scans.

5 Acknowledgements

This work was partially supported by the Bretagne region and by the National Research Agency (ANR) in the framework of Investissement d'Avenir Program through Labex (ANR-11-LABX-0004).

We thank Dr Antoine Lucas from University Hospital of Rennes for his help in understanding the clinical issues related to balloon angioplasty.

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