Image-based mechanical characterization of large blood vessels

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***Abstract*—Accurate planning of minimally invasive cardiovascular procedures such as percutaneous pulmonary valve implantation relies on a mechanical characterization of the material properties of the patient's implantation site. A non-invasive image-based framework able to perform this task is currently lacking. The aim of this study is to develop an image-based method able to extrapolate the mechanical properties of cardiovascular structures from Phase Contrast Magnetic Resonance Imaging (PC MRI). An experiment was set up on using cylindrical and patient-specific phantoms, which were 3D-printed and inserted in a mock circulatory loop (MCL) to simulate a simplified model of the cardiovascular system. PC MRI data were acquired and area and flow dynamic curves were obtained, allowing estimation of the Young's modulus (E) of the phantoms' material by using the flow-area (QA) loop method. Uniaxial tensile tests on the material were also performed to obtain direct measure of the material elasticity. Finally, finite element (FE) simulations were carried out with the aim to replicate the experiment, by coupling the sensors' information detected during the imaging acquisition and the material properties evaluated by QA loop method and tensile tests. MCL experiments and PC MRI acquisitions were feasible on TangoBlackPlus FLX980 phantoms. Areas and flows estimated by FE simulations well matched the PC MRI measurements. The estimation of the material characteristics by QA loop method was consistent with "gold standard" measurement, although further experiments are required to establish the correct framework.**

***Keywords*— image-based, MRI, FE, patient-specific.**

I. INTRODUCTION

PERCUTANEOUS pulmonary valve implantation (PPVI) was introduced [1] to handle several congenital heart valve pathologies by means of a minimally invasive approach. The planning of such intervention is currently based on imaging techniques as Magnetic Resonance Imaging (MRI) providing information on the anatomy and on the function of the implantation site. While MRI allows an accurate description of the implantation site, inferring the mechanical properties still represents a challenging task. Previous studies tried to combine finite element (FE) analysis and MRI to derive constitutive material parameters [2], [3]. However, a validated image-based method capable to infer the mechanical properties of vessel tissue is still lacking. Such a method would allow to predict the feasibility of the intervention by simulating accurately interactions between a certain device within a patient-specific geometry.

In this study, we developed an image-based experiment for the mechanical characterization of selected materials. The results can improve patient-specific modelling of PPVI and other cardiovascular interventions.

II. MATERIALS AND METHODS

An experimental mock circulatory loop (MCL) has been set up to test models of a blood vessel which were 3D-printed under cardiac pulsatile conditions, i.e. a hollow cylinder (150 mm length, 12.7 mm internal diameter and 2 mm thickness) and a patient-specific model of pulmonary artery.

The material used for the phantoms was TangoBlackPlus FLX980 (TP), a compliant material already employed to mimic arterial vessels [4]. The MCL was powered by a pulsatile pump (Harvard apparatus pulsatile blood pump) while flow and pressure information were measured by a flowmeter (ME 9PXL) and a catheter pressure (Opsens 9F).

The MCL circuit was positioned in the MRI scanner (Siemens Avanto 1.5 T) room in order to acquire Phase Contrast (PC) MRI of the phantoms, while sensors registered flow and pressure data by using a Biopac MP150. PC cross-sectional images (pixel size 1.17 mm, 40 temporal frames) were acquired in through plane modality in the middle of the cylindrical phantom and in three sections of the patient-specific phantom (proximal, stenotic and distal), with a VENC of 200 cm/s. Area and flow values were evaluated by a validated post-processing software (Segment 2.0).

The flow-area (QA) loop method, commonly applied on ultrasound (US) images [5], [6], was used to evaluate the material properties of TP in terms of Young's modulus (E). The QA loop method is based on the evaluation of the pulse wave velocity (PWV), evaluated as the slope of the linear part of the loop obtained by coupling flow and area information as obtained from imaging data. Then, wall cross-sectional area (WCSA) and cross-sectional distensibility (DC) are directly derived from PWV. From WCSA, DC, and the minimum area A of the phantom, the E value is computed as in Eq. (1).

$$E = \frac{3\left(1 + A/WCSA\right)}{DC} \tag{1}$$

The TP elastic modulus was also assessed by uniaxial tensile tests, conducted on fifteen 3D-printed TP dogbone-like specimens. For this purpose, an extensometer system has been set up, composed by: the testing machine (zwicki-Line Materials Testing Machine) to pull the samples; a camera (HD Webcam C525) for tracking the markers attached on the sample and a load cell (HBM S2M), respectively for the strain (ε) and stress (σ) evaluation.

Finally, FE simulations were conducted on the cylindrical model with the commercial software Abaqus 6.14-5 (Dassault Systèmes) to replicate the conditions of the MCL experiment by means of fluid-structural interaction (FSI) analyses. The solid part was meshed with 6000 elements, while the fluid part with 21000 elements. The simulations were run on the FE model by coupling the flow information registered by the flowmeter during the MRI acquisition and the material properties evaluated by both QA loop method and tensile tests in order to evaluate the differences between direct and indirect methods.

III. Results and Discussion

QA loop method applied to the segmentation results of PC images, of which a frame is given in Fig. 1, provided an E value estimation of 0.22±0.04 MPa.

The results of the tensile tests computed the E value as the average slope of the linear fitting curve for each σ-ε curve and found to be 0.50±0.02 MPa.

In FSI simulations, the flow and area dynamics were computed in the middle section of the FE cylindrical model. Fig. 2 shows a frame at maximum flow level of the model with E=0.50 MPa. FSI simulations for E=0.50 MPa showed a good agreement with area PC MRI measurements (4.63%) and an overestimation of flow (16.38%). For E=0.22 MPa there was an overestimation of both area (8.67%) and flow (20.67%). Flow and area dynamic curves evaluated from both PC imaging segmentation and FSI simulations for E=0.50 MPa are compared in Fig. 3.

Results of this preliminary study were encouraging, even if they show differences between image-based methods, tensile tests and FE analyses. The E value computed from the QA loop method appeared to be underestimated, considering the results from tensile tests, confirmed by the FSI simulations' results. Further investigations should be conducted in order to assess the reasons of such differences. In particular, a further evaluation of the QA loop method should be carried out comparing its use on US images, on which the QA loop method is validated, and MRI data. Furthermore, others rubber-like materials could be tested, following the same flowchart of this work, also modeling more complex geometries such as patient-specific, with the final aim of developing an image-based framework able to characterize the mechanical behavior of a patient-specific vessel, which would lead to new modeling environments for predictive, individualized healthcare.

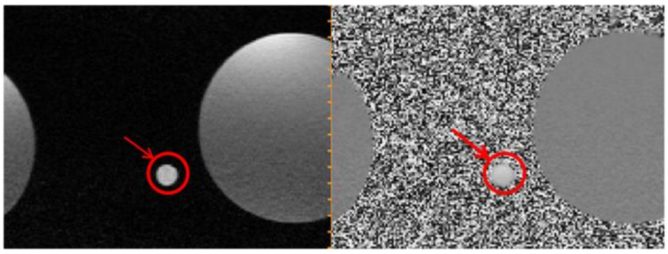

Fig. 1 - Cross-sectional single frame PC image of cylindrical phantom (highlighted), both magnitude (left) and phase (right).

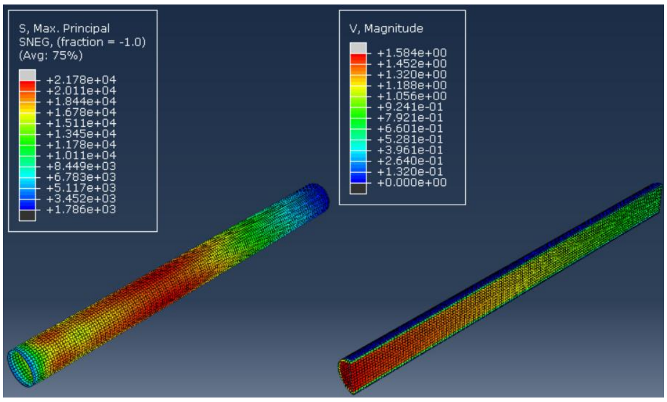

Fig. 2 - Deformed shape of the FSI cylindrical model, both solid (left) and fluid (right) parts, at maximum flow level, by assigning E=0.50 MPa. In the color bar, stress are given in Pa, while velocities in m/s.

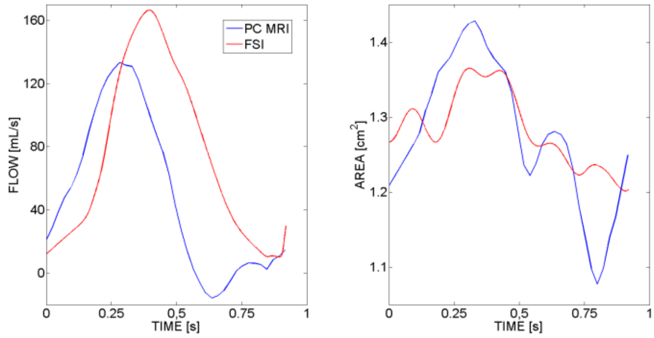

Fig. 3 - Left: flow curves evaluated from imaging segmentation (blue) and FSI simulation (red) for E=0.50 MPa. Right: same for area curves.

IV. Conclusion

In this work, an experimental set-up has been developed in order to test a selected material for the inferring of its mechanical properties by means of PC MRI, combining experimental and computational tools.

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References

[1] P. Bonhoeffer, Y. Boudjemline and Z. Saliba, *Percutaneous replacement of pulmonary valve in a right-ventricle to pulmonary-artery prosthetic conduit with valve dysfunction.* The Lancet, vol. 356, pp. 1403-1405, 2000.

[2] G. M. Bosi, C. Capelli, S. Khambadkone, A. M. Taylor and S. Schievano, *Patient-specific finite element models to support clinical decisions: a lesson learnt from a case study of percutaneous pulmonary valve implantation*. Catheterization and Cardiovascular Interventions, vol. 26, pp. 1120-1130, 2015.

[3] V. Flamini, A. P. Creane, C. M. Kerskens, C. Lally, *Imaging and finite element analysis: A methodology for non-invasive characterization of aortic tissue*. Medical Engineering & Physics, vol. 37, pp. 48-54, 2015.

[4] G. Biglino, P. Verschueren, R. Zegels, A.M. Taylor and S. Schievano, *Rapid prototyping compliant arterial phantoms for in-vitro studies and device testing*. Journal of Cardiovascular Magnetic Resonance 2013, 15:2.

[5] R. Williams, A. Needles, E. Cherin, Y. Q. Zhou, R. M. Henkelman et al., *Noninvasive ultrasonic measurement of regional and local pulse-wave velocity in mice*. Atherosclerosis journal, vol. 237, pp. 31-37, 2014.

[6] N. Di Lascio, F. Stea, C. Kusmic, R. Sicari and F. Faita, *Non-invasive assesment of pulse wave velocity in mice by means of ultrasound images*. Atherosclerosis, vol. 237, pp. 31-37, 2014.