A combined *in silico* and *in vitro* image-based approach for the mechanical characterization of patient-specific cardiovascular structures

B.M. Fanni[1], S. Celi[1], E. Gasparotti[1], E. Vignali[1], K. Capellini[1], S. Schievano[2], L. Landini[1,3], C. Capelli[2] and V. Positano[1]

[1] BioCardioLab, Bioengineering Unit, Fondazione Toscana Gabriele Monasterio, Massa, Italy
[2] Institute of Cardiovascular Science, University College of London, London, United Kingdom
[3] Department of Information Engineering, University of Pisa, Pisa, Italy

Introduction

In the context of minimally invasive cardiovascular interventions, current imaging techniques allows an accurate geometrical description of the implantation site, while inferring its mechanical properties still represents a challenging task [1]. Efficacy of such interventions relies also on the capability to predict the mechanical interaction between the device and the implantation site by means of numerical simulations (Fig. 1).

Aim – This study proposes a novel framework able to infer the mechanical properties of patient-specific blood vessels from Phase Contrast Magnetic Resonance Imaging (PC-MRI) analysis.

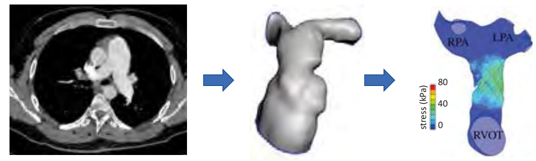

Figure 1 – Theoretical pipeline leading from imaging to simulation

Material and Methods

An experimental mock circulatory system (MCS) was developed to mimic a simplified cardiovascular system under simulated pulsatile conditions (Fig. 2a). The MCS was properly placed inside the MR scanner to acquire cross-sectional PC-MRI data of two 3D printed models, i.e. a pipe phantom and a pulmonary artery (PA) phantom (Fig. 2b), while sensors measured flow and pressure data. The 3D printing material was TangoBlackPlus FLX980 (TP). Flow-area loop (QAL) method [2] was applied on both phantoms and real patient PC-MRI post-processing data to estimate the Young's modulus (E) of TP and patient-specific PA. E value was also assessed conducting standard uniaxial tensile tests (Fig. 4). Fluid-structure interaction simulations were run for both *in vitro* and *in vivo* models (Fig. 5) to evaluate the predictive capability of the image-based framework in terms of area deformation.

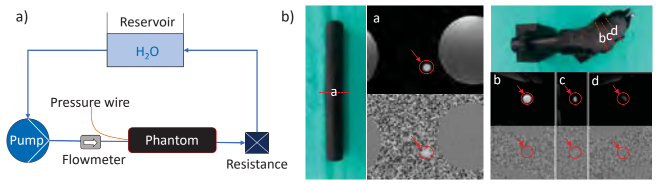

Figure 2 – a) MCS scheme b) pipe (left) and PA (right) phantoms with PC-MRI cross-sections

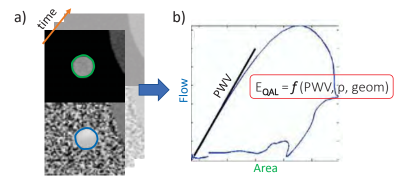

Figure 3 – From imaging (a) to E value (b)

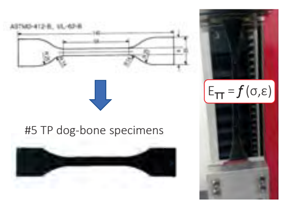

Figure 4 – Uniaxial tensile tests set-up

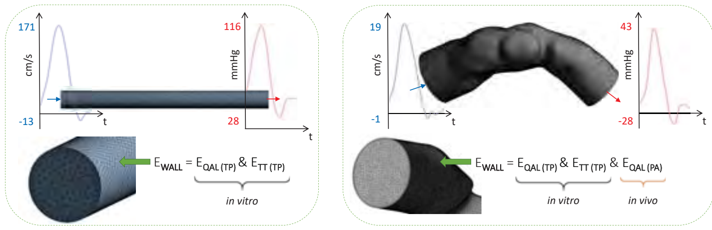

Figure 5 – FSI simulations set-up for pipe model (left) and pulmonary artery model (right)

Results

QAL method provides an E value of 0.22±0.04MPa (Fig. 6a) while mechanical testing resulted in E=0.50±0.02MPa (Fig. 6b). Results of FSI simulations were evaluated in the same cross-sections of PC-MRI data in order to compare in silico and imaging results, i.e. middle section for the pipe phantom and proximal, stenotic and distal sections for PA phantom, while for the clinical case, the compared section was sited 1cm after the valve level. For the pipe phantom, a difference of -2.97% was found by assigning E=0.5MPa, while for E=0.22MPa the error was 15.47% (Fig. 7). For the PA phantom, the assignation of E=0.5MPa led to an error of 16.41%, while a difference of -4.91% was found for E=0.22MPa (Fig. 8). For the *in vivo* case, E value resulted in 0.06MPa and the relative difference between numerical and imaging results was -6.18% (Fig. 9).

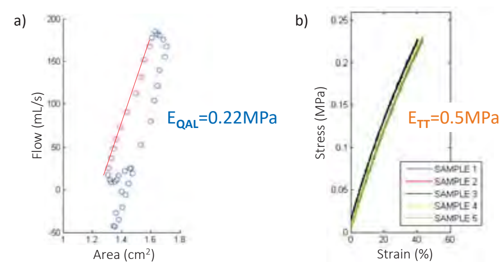

Figure 6 – E values obtained from QAL method (a) and tensile tests (b)

IN VITRO

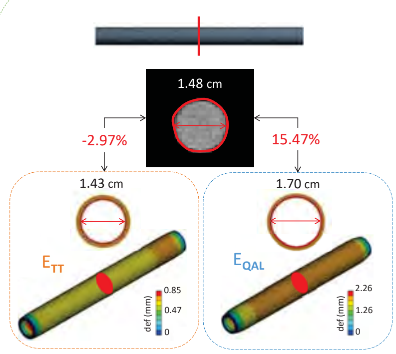

Figure 7 – Comparison between FSI results with E_{TT} and E_{QAL} and PC-MRI middle cross-section for pipe phantom

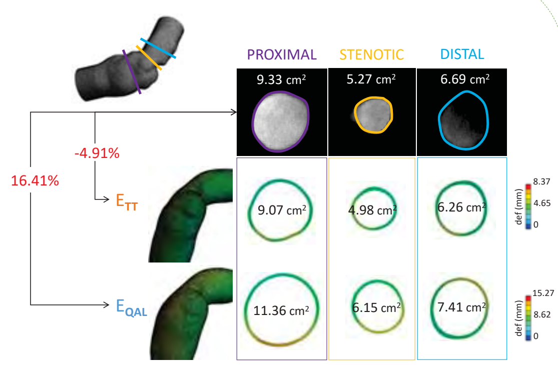

Figure 8 – Comparison between FSI results with E_{TT} and E_{QAL} and PC-MRI proximal, stenotic and distal cross-sections for PA phantom

IN VIVO

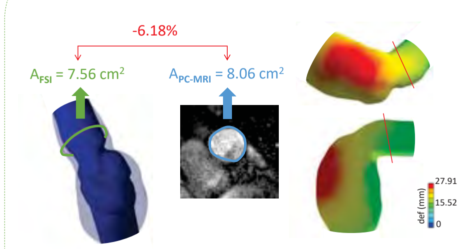

Figure 9 – Comparison between FSI results with E_{QAL} and PC-MRI cross-sections for the clinical case

Conclusions – Results of this preliminary study were encouraging, even if they show differences between image-based method, tensile tests and FSI results. The E value computed from the QAL 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 QAL method should be carried out comparing its use on US images, on which the QAL method is validated, and MRI data. Furthermore, others rubber-like materials could be tested, following the same flowchart of this work, 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.

References

[1] B.M. Fanni et al, Proceedings of the VII Annual Meeting Italian Chapter of the ESB 2017:35.
[2] N. Di Lascio et al, Atherosclerosis 237 (2014) 31-37.

Contact Information

bmfanni@ftgm.it
s.celi@ftgm.it
bcl.ftgm.it

Acknowledgements – This works is supported by VIVIR (Italian Ministry of Health) projects funding