A novel image-based formulation for enhanced patient-specific *in silico* simulations of cardiovascular interventions

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

[1]BioCardioLab, Bioengineering Unit, Fondazione Toscana Gabriele Monasterio, Massa, Italy

[2]Department of Information Engineering, University of Pisa, Pisa, Italy

[3]UCL Institute of Cardiovascular Science, University College of London, London, United Kingdom

Introduction

Computational models have been widely developed over the last decades to understand the mechanics and fluid dynamic of cardiovascular structures [1]. However, the translation of computational models into clinical applications, such as planning of procedures, is still scarce and limited to few case-reports [2]. Major challenges are the adaptation of computational models into patient-specific clinical conditions. while current imaging techniques can provide high resolution information to derive both 3D models of patient-specific anatomies and boundary conditions, the *in vivo* characterization of reliable patient-specific mechanical properties still represents the biggest source of uncertainty.

The **aim** of the study is to propose a **novel formulation** to estimate basic ***in vivo* mechanical properties** (Young's modulus **E**) of vessel's walls in a **non-invasive** and **image-based** way.

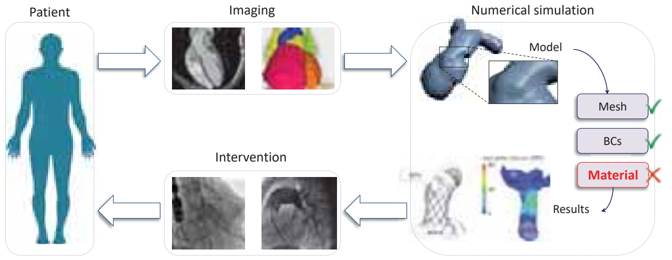


Fig. 1 – Scheme showing how numerical simulation can be used in a clinical workflow to enhance the efficacy of interventions. An in vivo characterization of the patient-specific material would improve such pipeline

Materials and Methods

I. Image-based method – The QA method [3] is used to estimate the pulse wave velocity (**PWV**) based on the analysis of phase contrast magnetic resonance imaging (PC MRI) data (Fig. 2).

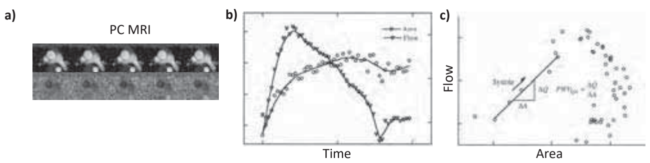


Fig. 2 – **a)** PC MRI sequence; **b)** Area and flow values as derived from the PC MRI segmentation; **c)** QA loop and calculation of the PWV as the slope of the linear fitting of the points belonging to the early systole of the cardiac cycle.

II. Formulation – The formulation proposed for the estimation of the E value is given by:

$$E = 3\,\kappa\,PWV^2\left(1+\frac{A_0}{WCSA}\right) \quad (1)$$

where A_0 is the cross-sectional area of the vessel and WCSA is the wall-cross sectional area, both measured at diastole.

The κ parameter was a correction factor introduced in a previous study [4]:

$$\kappa = RAC\,\gamma \quad (2)$$

where RAC is the relative area change and γ is a constant.

III. *In silico* tests –Two-way FSI simulations of a vessel model were set up with different E values for the wall (Fig. 3). Eq. (1) was applied on the FSI datasets to estimate the E values.

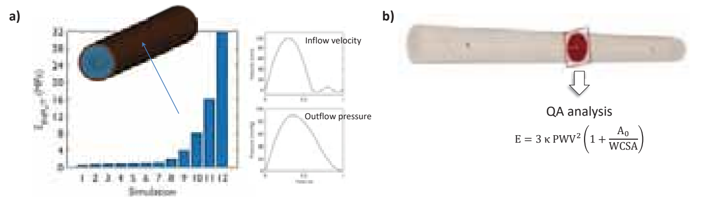


Fig. 3 – **a)** Vessel model for the FSI simulation and E values assigned to the wall; b) middle-cross section from which area and flow values were extracted and inputted for the QA analysis.

IV. *In vitro* experiments – Two phantoms were 3D printed (Fig. 4a) and inserted in an ad-hoc mock circulation system to acquire PC MRI and validate the QA analysis with tensile tests (Fig. 4).

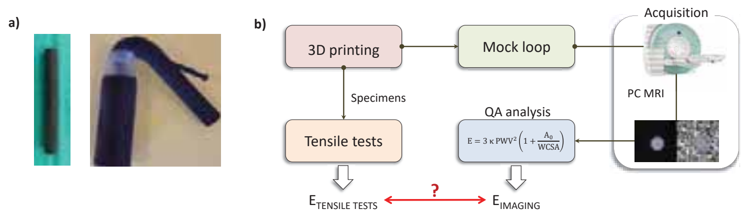


Fig. 4 – **a)** 3D printed phantoms; **b)** Workflow of the *in vitro* experiments.

V. *In vivo* patient-specific case – The presented workflow was also applied to a retrospective patient-specific case of a percutaneous pulmonary valve implantation (PPVI) to assess the predictive capability of the proposed method (Fig. 5) after finite element method (FEM) simulation of the intervention.

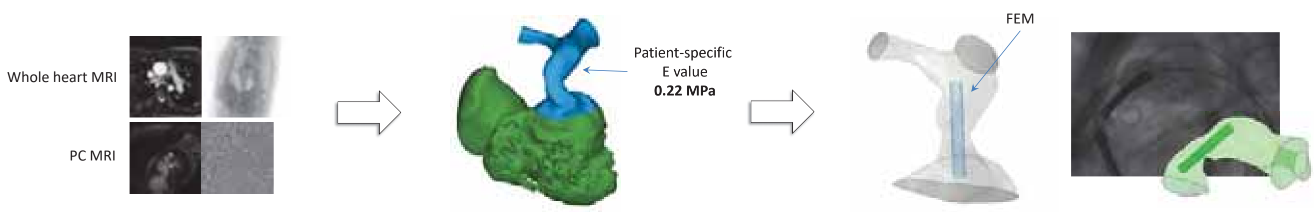
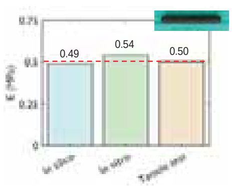


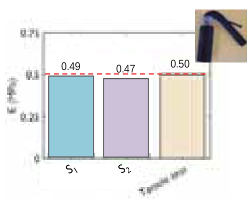
Fig. 5 – ***In vivo* patient-specific workflow**.

Results

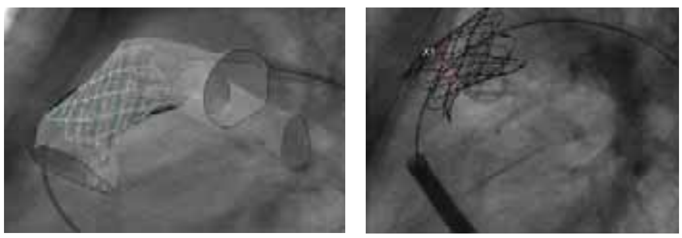
In silico – An excellent matching between the input E values and the inferred ones, with an average error of 7.8%.

In vitro – Direct (tensile tests) and indirect (QA method) evaluation of the E value well matched:





In vivo – Post-operative fluoroscopy and FEM results showed high agreement:



Conclusion

A novel image-based formulation for the inferring of patient-specific material properties was here presented. The method was successfully tested in silico and validated in vitro. The preliminary results of the in vivo case demonstrated the feasibility of the method to be applied on patient-specific scenarios. Such a method would facilitate the translation of computational tools in clinics.

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Contacts: bmfanni@ftgm.it
bcl.ftgm.it

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