IMPLEMENTING DIGITAL TWINS OF THE CARDIOVASCULAR SYSTEM IN CLINICAL SETTINGS: AN AUTOMATED DEEP LEARNING PIPELINE

Martino Andrea Scarpolini (1,2), Marilena Mazzoli (1,3), Simone Garzia (1,3), Angelo Monteleone (4) and Simona Celi (1)

1. BioCardioLab, Fondazione Toscana Gabriele Monasterio, Italy; 2. University of Rome "Tor Vergata", Italy 3. Department of Information Engineering, University of Pisa, Italy; 4. Clinical Imaging Department, Fondazione Toscana Gabriele Monasterio, Italy.

Introduction

Cardiovascular diseases (CVDs) are a leading cause of death in Europe, accounting for 45% of all deaths [1]. The adoption of computational power and numerical tools has advanced the development of digital twins for CVDs, but their high computational cost and time have limited their implementation in clinical settings. In this work, we propose a workflow that combines deep learning, reduced order modelling (ROM) and computational fluid dynamics (CFD) to automatically build a digital twin of the patient's thoracic aorta.

Material and methods

The framework starts with the segmentation of CT scans to create a 3D model of the patient's thoracic aorta, including supra-aortic vessels and the aortic root. To achieve this (Figure 1), a UNet-based [2] neural network (NN) was trained using a dataset of 50 aortas that were manually segmented from patient-specific CT scans. Using this NN, a first step (raw) segmentation can be automatically obtained. Additionally, a statistical shape model (SSM) was created from the dataset to capture the morphological features of each aorta. The SSM can evaluate the similarity between the newly segmented aortas and the ones from the dataset. Moreover, it serves as a refinement step for the raw segmentation provided by the NN. The statistical information with the patient-specific information from the CT scan are integrated to obtain a high-fidelity segmentation. Finally, hemodynamic indices such as time averaged wall shear stress (TAWSS) can be estimated either performing a CFD simulation, or using a machine learning-based ROM trained on a large scale CFD dataset. The decision can be quantitatively taken based on the shape analysis. The large scale CFD dataset is created by performing transient CFD simulations on 400 synthetic aortic geometries generated using the SSM. The volumetric mesh for CFD simulations is automatically generated through an in-house python script based on ANSA. Each synthetic geometry has its own Windkessel parameters (optimised on the basis of inlet/outlet surface areas) in order to dynamically adjust the pressure at each outlet according to physiological values.

Results

Figure 1 shows the workflow applied to a test CT scan. The first-step automatic segmentation performed through the NN reaches a mean dice score of 0.93 compared to the manual one. Furthermore, the integration with the SSM can eliminate potential errors from the 3d model surface mesh. Regarding the DL-based ROM, a mean absolute error of 5% for the TAWSS, compared to CFD, is reached. Following the statistical shape analysis, if a new aorta is morphologically strongly different from the ones in the dataset, a full-order CFD simulation is performed in order to control the error on the estimated hemodynamic indices. This workflow allows to extract patient-specific information about the thoracic aorta from a CT scan of a patient almost real-time (~30 sec.).

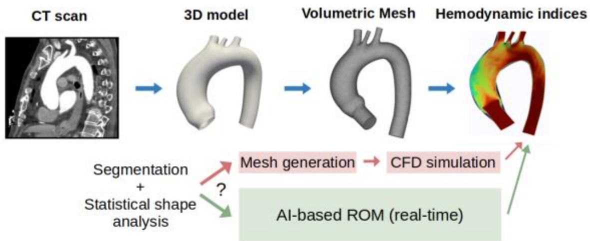

Figure 1: Entire workflow: first, a segmentation and statistical shape analysis is performed. Secondly, to extract hemodynamic indices either a full-order CFD simulation (red path) or a reduced order modelling approach can be used (green path).

Discussion

A completely automated workflow for the construction of a digital twin of the thoracic aorta has been developed with a significant speed improvement that enables the potential application in clinical environments, without significant loss of accuracy.

References

1. Group et al, Eur. Heart J. 39(7), 508–579 (2017).
2. Ronneberger et al, MICCAI 234-241 (2015).
3. Thamsen et al, IEEE Trans Med Im 40(5), 1438-1449 (2021).
3. Verma et al, Proceedings of the CVPR 2598-2606 (2018).

Acknowledgments

This project has received funding from the Marie Skłodowska Curie grant agreement No 859836.