FSI-BASED DIGITAL TWIN FOR AORTIC GRAFT OPTIMIZATION: A FULLY AUTOMATED PIPELINE FOR PATIENT-SPECIFIC SIMULATIONS

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Introduction

Ascending aorta (AA) surgical grafting is a well-established treatment for aortic aneurysms and dissections. However, it can have adverse and life-threatening long-term effects, such as dissection of the descending aorta (DA) distal to the implanted graft [1]. Compliance mismatch between the graft and the native aorta is regarded as one of the main risk factors for late adverse events [2], as it alters the hemodynamics downstream from the graft, potentially contributing to disease progression [3].

Fluid-Structure Interaction (FSI) simulations provide valuable insights into the complex interplay between flow and aortic wall. Nevertheless, existing approaches are largely operator-dependent and time-consuming [4]. Herein, we propose a fully automated workflow encompassing all patient-specific characteristics: six simulations were designed to first identify the compliance values that minimize adverse hemodynamic effects in the DA and subsequently validate the impact of graft compliance on postoperative outcomes.

Material and Methods

For each patient MRA, 4D flow MRI, and cine-MRI scans were acquired both before and after surgery. The preoperative images were used to simulate aortic biomechanics in four scenarios corresponding to different compliances: (i) diseased AA compliance, (ii) healthy DA compliance, (iii) Dacron graft compliance, and (iv) intermediate compliance (average of ii and iii). Additionally, two postoperative simulations were conducted to model the implant of (v) a Dacron graft and (vi) a more compliant electrowritten graft.

Figure 1 shows the automated pre-processing pipeline used for setting up the simulations. The thoracic aorta, including the supra-aortic vessels, was reconstructed from MRA images and meshed using an in-house Python code. The patient-specific inlet velocity profile was derived from 4D flow MRI, while outlet boundary conditions were modelled with a three-element Windkessel tuned to match in vivo measured systolic and diastolic pressures. Aortic wall tissue was modelled as incompressible, hyperelastic, and anisotropic with different properties assigned to the AA, the aortic arch, and the DA. Region-specific compliance values were extracted from cine-MRI data, while the material parameters were determined by fitting constitutive models from the literature to the measured compliance.

All simulations were run on the open-source finite-element solver Simvascular [5]. A fluid dynamic simulation computed the intraluminal pressure field, applied as a boundary condition in a structural simulation to determine prestress distribution. These results initialized the final FSI simulation.

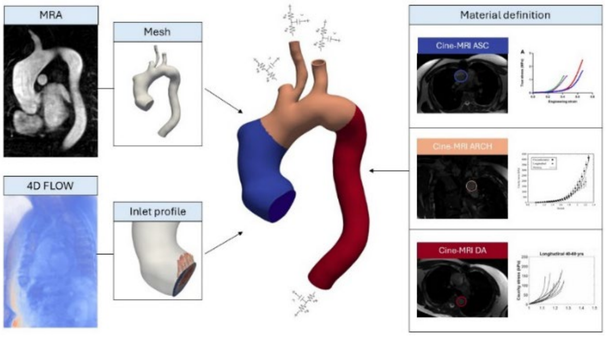

Figure 1: Schematic representation of the workflow developed to build a patient-specific model.

Results

The entire workflow had an average runtime of approximately 5–6 days. Preliminary results show that Wall Shear Stress (WSS) distributions varied across different simulations, with peak values ranging from 5 to 16 Pa. Preoperative simulations identified case (ii), i.e lower compliance value, as having the lowest WSS in the DA. In the postoperative simulations, implantation of a Dacron graft (v) yielded the highest WSS values in the DA due to the increased AA stiffness and a higher inlet velocity profile. In contrast, the implantation of a more compliant electrowritten graft (vi) resulted in lower WSS values in the distal regions.

Discussion

The novel workflow herein proposed enables the execution of multiple simulations for a large cohort of patients significantly reducing computation time compared to previous studies [4]. Pre-op simulation results allow for the identification of the compliance values that minimize WSS in the DA.

Furthermore, postoperative simulations confirm that an electrowritten graft with a compliance closer to that of an healthy aorta effectively reduces WSS in the distal regions, thereby decreasing the likelihood of long-term adverse events.

References

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