11º CONGRESSO NACIONAL DE BIOMECÂNICA
A. P. G. Castro, C. Pina, P. R. Fernandes, C. Santos, J. Folgado & A. Amaro (Eds)
Sesimbra, Portugal, 21-22 de Fevereiro, 2025

ON THE RELEVANCE OF USING FLUID-STRUCTURE INTERACTION TO MODEL ASCENDING THORACIC AORTIC ANEURYSMS

André Mourato[1], Rodrigo Valente[1], José Xavier[1,2], Moisés Brito[1,2], Stéphane Avril[3], António C. Tomás[4], José Fragata[4,5]

[1] UNIDEMI, NOVA School of Science and Technology, Portugal

[2] Intelligent Systems Associate Laboratory, Portugal

[3] Inserm, Sainbiose U1059, École des Mines de Saint-Étienne, France

[4] Department of Cardiothoracic Surgery, Santa Marta Hospital, Portugal

[5] Department of Surgery and Human Morphology, NOVA Medical School, Portugal

af.mourato@campus.fct.unl.pt; rb.valente@campus.fct.unl.pt; jmc.xavier@fct.unl.pt; moisesbrito@fct.unl.pt; avril@emse.fr; acruztomas@gmail.com; jigfragata@gmail.com

KEYWORDS: Ascending thoracic aortic aneurysm, computational fluid dynamics, computational solid mechanics, fluid-structure interaction, reduced order modelling

1 INTRODUCTION

Over the past few decades, numerical modelling has emerged as a solution to improve current clinical guidelines for the diagnosis and treatment of Ascending Thoracic Aortic Aneurysms (ATAAs) [1,2]. While the maximum diameter criterion remains effective, it fails to accurately stratify the risk of aortic rupture for every patient. Despite the potential of computational frameworks, the extensive reporting time limits their application in clinical practices. This work aims to test whether more straightforward approaches, such as Reduced Order Models (ROM), Computational Fluid Dynamics (CFD) or Computational Solid Mechanics (CSM), can predict the biomechanics of ATAAs as accurately as Fluid-Structure Interaction (FSI).

2 MATERIALS AND METHODS

The numerical models were developed using patient-specific data obtained via Computational Tomography Angiography (CTA) and 4D flow Magnetic Resonance Imaging (MRI). The medical imaging exams were performed on a 48-years-old female with ATAA and a bovine arch. The CTA data was imported into the 3D Slicer open-source software to generate the virtualisation of the fluid domain. This virtualisation was then used to generate the solid domain, assuming a homogeneous thickness of 1.8 mm. The haemodynamic modelling was performed by considering blood as a Newtonian and incompressible fluid, and the flow as laminar. The boundary conditions were defined using MRI data. At the inlet, a patient-specific flow rate was assumed. Three-element Windkessel models were applied at the outlets and tunned to fit a pressure variation of 80-120 mmHg. Regarding the CSM models, the aortic wall was modelled as a Neo-Hookean, isotropic, incompressible and prestressed material. A pressure boundary condition was applied to the inner surface of the solid domain, corresponding to the results of the haemodynamic simulations. In total, 8 simulations were performed. The numerical results of the FSI model were considered as reference and analysed in terms of: (i) nodal pressure evolution (compared using the Pearson's correlation coefficient, R); (ii) Time-Averaged Wall Shear Stress (TAWSS); (iii) maximum principal stress, σ_P^M; and (iv) maximum principal strain, ε_P^M.

3 Results and Discussion

The results of pressure field, TAWSS, maximum principal stress and strain are presented in Figure 1. The rigid and moving wall CFD models presented a good agreement with FSI regarding the estimated pressure (average R of 0.97). However, the statistical distribution of TAWSS differed significantly from the reference. Using ROM provides accurate estimations of pressure evolution ($R > 0.99$) but is unreliable regarding estimating TAWSS. Performing CSM analysis with CFD driven boundary conditions leads to overestimations of the maximum principal stress and strain. Nonetheless, coupling CSM and ROM driven boundary conditions presented a close agreement with FSI. Another relevant aspect is the time required to achieve convergence. In this regard, the ROM simulations are the most efficient requiring around 4 min. The rigid wall and moving wall simulations were equivalent and required 100 and 120 hours, respectively. The FSI simulations, as expected, required the most time to achieve convergence (250 hours). All CSM simulations required around 24 hours.

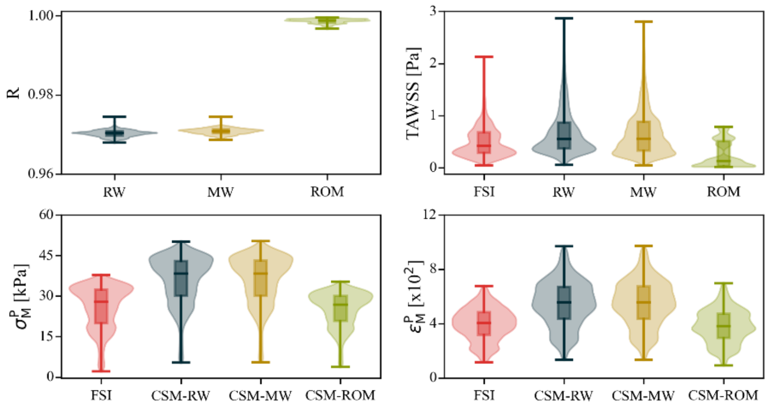

Figure 1 - Impact of using FSI on the numerical modelling of ATAA: violin plots of the Pearson's correlation coefficient of the nodal pressure, R, TAWSS, maximum principal stress, σ_P^M, and maximum principal strain, ε_P^M, estimated by FSI, rigid and moving wall CFD, ROM and CSM models.

4 Conclusions

In this work, the relevance of modelling the interplay between blood and ATAA wall was evaluated. The results suggested that wall motion does not significantly impact the pressure field estimations. However, FSI remains the gold standard to estimate WSS magnitude. The coupling CSM and pressure boundary conditions obtained via ROM simulations showed a close agreement with FSI in estimating ATAA wall mechanics.

Acknowledgments

This research was funded by the Portuguese Foundation for Science and Technology (FCT,IP) under the projects: "Fluid-structure interaction for functional assessment of ascending aortic aneurysms: a biomechanical-based approach toward clinical practice" (AneurysmTool) 10.54499/PTDC/EMD-EMD/1230/2021; UNIDEMI: UIDB/00667/2020 and UIDP/00667/2020; A. Mourato Ph.D. grant 10.54499/UI/BD/151212/2021, R. Valente Ph.D. grant 2022.12223.BD.

References

[1] J. K. Long, R. W. Liu, D. Ma, L. Shi, S. C. Ho and D. Wang, "Pulsatile hemodynamics in patient-specific thoracic aortic dissection models constructed from computed tomography angiography", Journal of X-ray Science and Technology, vol. 25, pp. 233-245, Jan 2017.

[2] K. Capellini, E. Vignali, E. Costa, E. Gasparotti, M. E. Biancolini, L. Landini et al., "Computational fluid dynamic study for aTAA hemodynamics: an integrated image-based and radial basis functions mesh morphing approach", Journal of Biomechanical Engineering, vol. 140, pp. 111007, Aug 2018.