2024-1 | 49th congress of the Société de Biomécanique
29-31 octobre 2024, Compiègne, France

Multidisciplinary Biomechanics Journal

Aortic displacement reconstruction to build a patient-specific computational model

Marc Baudouard[a], Carine Guivier-Curien[a*], Stanislas Rapacchi[b], Alexis Jacquier[c], Valérie Deplano[a]

a IRPHE UMR 7342, AMU, CNRS, ECM, France
b CRMBM UMR 7339, AMU, CNRS, France
c Hôpital la Timone, AP-HM, CRMBM, France
* Corresponding author: carine.guivier@univ-amu.fr

Received date: 07/04/2024
Accepted date: 28/06/2024
Publication date: 31/01/2025

Keywords: thoracic aneurysm, MRI, numerical modelling, aortic wall displacement

1. Introduction

Thoracic aortic aneurysm (TAA) is a pathology of the aortic wall leading to an abnormal increase in arterial lumen diameter. Several clinical questions still remain regarding its optimal management especially in prediction of evolution. Biomechanical studies can provide some relevant insights to help move forward on these issues. To this end, numerical studies remain a means of assessing biomechanical parameters known to be linked to long-term remodeling, such as wall shear stress (WSS). Numerical modelling actually provides sufficient spatial and temporal resolution to correctly access these variables of interest. The greatest difficulty is to be able to propose a patient-specific model that is compatible with clinical practice in terms of calculation time. The most advanced numerical simulations include fluid-structure interactions (FSI) between the blood flow and the aortic wall (Vignali et al. 2022). However, in addition to the high computational times required, the aortic wall behavior is rarely patient-specific. Magnetic resonance imaging (MRI) gives access to information about the aorta motion that can be used to overcome these hindrances. The objective of our study is thus to propose a way to combine all patient-specific information from MRI in an efficient and relevant numerical modelling with minimal computational costs. The key point of this work is the integration of the aortic wall motion as fluid boundary conditions of a patient-specific numerical model.

2. Methods

4D flow MRI, 2D steady-state free precession cine MRI and 2D flow MRI were performed on 3 patients with TAA, through a specific protocol defined in concertation with radiologists. The overall method consists in reconstructing aortic displacement from a segmentation of a 3D geometry of reference, and 6 specific 2D contours segmented both in space and time with the highest resolution that could be reached.

2.1 Extraction of reference geometry and centerline

From the velocity magnitude map computed from 4D flow MRI data, the lumen of the thoracic aorta at peak flow time was segmented in GTFlow software with a region-growing method. Sub-segmented zones due to low velocities were manually rectified to ensure a correct reconstruction. Spatial resolution of 4D flow MRI was about 2.1mm. Pre-processing included noise masking, corrections for phase aliasing and concomitant gradients. The obtained 3D segmentation constituted the reference geometry, from which the CenterLine of reference (CLref) was extracted.

2.2 Segmentation of specific contours

2D cine MRI allowed to obtain 6 contours chosen in concertation with clinicians to be representative of the overall patient specific morphology and especially his/her aneurysmal zone. Spatio-temporal resolutions were 1.1mm and about 25ms. Contours were segmented using active contours in MatLab software (Figure 1A).

To cite this article: Marc Baudouard, Carine Guivier-Curien, Stanislas Rapacchi, Alexis Jacquier, Valérie Deplano, Aortic displacement reconstruction to build a patient-specific computational model, *Multidisciplinary Biomechanics Journal*, 2024, vol. 1, p. 113-115, DOI: 10.46298/mbj.14485.

2.3 Spatial and temporal aortic displacement reconstruction

From the CLref and segmented contours, MatLab code was developed to reconstruct the aortic displacement in space and time. Point of intersection between CLref and contour plane was identified as center of contours at peak flow time. The cyclic displacement of the contours' centers is spatially interpolated (piecewise cubic hermite interpolating polynomial) along the arc length of the CLref to obtain the complete CL displacement for all time phases. For each time phase, an initial cylindrical envelope of contours around corresponding CL was formed and then deformed to match the true vessel contours at imaging planes recorded at this time. Displacement of the envelopes allows to compute the spatio-temporal displacement field, which is applied to the reference geometry to obtain a geometry for all time phases (Figure 1B).

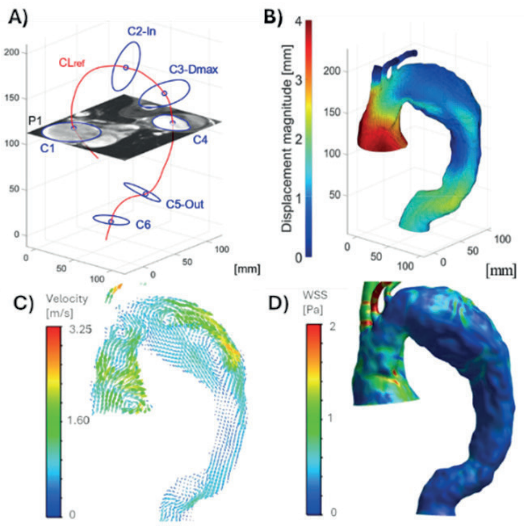

Figure 1. Illustration of results for patient 1.

A) Aortic reconstruction from CLref, and 6 2D cine MRI segmented contours. B) Displacement of the aorta at the maximum volume. C) Example of a velocity vector field. D) Example of WSS map.

2.4 Numerical modelling

Finally, to propose a relevant numerical modelling, inlet and outlet velocities were obtained from 2D flow MRI on the specific planes. Processing treatment was performed to respect mass conservation all along the cycle regarding the volume evolution defined through aortic displacement reconstruction. In the descending aorta, outlet velocities were injected into 3 element Windkessel equation to get a pressure profile over time. Fluid was modelled with a Carreau-Yasuda law. Flow is laminar and unsteady. Patient-specific period of the cardiac cycle was taken to set up a mesh whose element size was small enough to capture the viscous layer.

3. Results and discussion

For each patient, we obtain a spatial and temporal evolution of the aortic wall all along the cardiac cycle. Ranges of distension (variation of diameter) that we found are consistent with some previous observations: in Weber et al. (2009), distension in ascending aorta was 2.8 ± 0.7 mm and we found a maximum distension of 2.3mm at the same level in this study.

Thanks to 4D flow MRI exploitation of planes specifically defined midway between vessel contours and far from CLref phase, we validate our method: mean deviation on wall position between the validation contours and the reconstruction was always below 1.1 mm which is smaller than the 4D flow MRI resolution. Even if some further investigations have to be done to generalize the method, the protocol used to choose planes of interest appears correct for the patients included. Few previous works already proposed similar methods, but they were either limited to the ascending aorta (Calo et al. 2023) or the spatial resolution was higher (1.7mm for Lantz et al. 2014) and applied on heathy aorta. However, for patients and/or aged persons whose distension may be lower than for young healthy aorta, such a spatial resolution of 1.7mm is too small and thus unsuitable. Considering uncertainty due to spatial resolution, we found that the lowest significant distension that could be measured in this study was about 1.5mm.

A computational fluid dynamics model has then been built using patient-specific boundary conditions including wall motion, showing the feasibility of the method to be used to dedicated biomechanical study (Figure 1C and 1D). In addition to being patient-specific, the method offers drastic time savings compared to FSI simulation with a reduction factor of at least 2. Our method also allows to consider the global motion of the aortic root whereas in FSI at least one point of the aortic inlet face must be fixed.

4. Conclusions

Through specific developed MatLab code and with GTFlow software, we were able to propose an innovative method to reconstruct aortic displacement with the best spatio-temporal compromise obtained with clinical MRI sequences. This method has led us to propose patient-specific models for more in-depth biomechanical studies.

Conflict of interest

None.

References

Calò, K., Capellini, K., De Nisco, G., Mazzi, V., Gasparotti, E., Gallo, G., Celi, S., & Morbiducci, U. (2023). Impact of Wall Displacements on the Large-Scale Flow Coherence in Ascending Aorta. *J Biomech*, 154:111620. doi: 10.1016/j.jbiomech.2023.111620

Lantz, J., Dyverfeldt, P., & Ebbers, T. (2014). Improving Blood Flow Simulations by Incorporating Measured Subject-Specific Wall Motion. *Cardiovasc. Eng Tech* 5(3):261–69. doi: 10.1007/s13239-014-0187-5

Vignali, E., Gasparotti, E., Celi, S, & Avril, S. (2021). Fully-Coupled FSI Computational Analyses in the Ascending Thoracic Aorta Using Patient-Specific Conditions and Anisotropic Material Properties. *Front. Phys.*,12.doi: 10.3389/fphys.2021.732561

Weber, T.F., Ganten, M.K,.Böckler,D., Geisbüsch, P., Kopp-Schneider,A., Kauczor H.U., & von Tengg-Kobligk, H. (2009). Assessment of Thoracic Aortic Conformational Changes by Four-Dimensional Computed Tomography Angiography in Patients with Chronic Aortic Dissection Type b. *Eur Radiol*, 19(1):245–53. doi: 10.1007/s00330-008-1103-x