From Imaging to Simulation: A framework applied to simulate the blood flow in the carotids

R. Arís[1], V. Mani[2], H. Dyvorne[2], M. Jowkar[1], A. Santiago[1], G. Houzeaux[1], Z. Fayad[2], M. Vázquez[1]
[1]Barcelona Supercomputing Center (BSC), Spain
[2]Translational and Molecular Imaging Institute (TMII), The Mount Sinai Hospital, USA

ruth.aris@bsc.es

Abstract*-In this work we present a methodology to extract information from medical imaging and use it for hemodynamical simulation in arteries. Based on in-vivo magnetic resonance images (MRI), the velocity of the blood flow has been measured at different positions and times. Also, the anatomy of the vessel has been converted into a volume mesh suitable for numerical modeling. This data has been used to solve computationally the dynamics of the fluid inside the artery in healthy and pathologic cases. As an application, we have developed a computational model within the carotids. The next step in the pipeline will be to extend the simulation to fluid-structure interaction (FSI) to find the parameters in an atherosclerotic plaque that could lead to rupture.*

INTRODUCTION

The complex structure of an atherosclerotic plaque affects the dynamics of the fluid inside the vessel. Usually, it is composed of different materials such as a lipid pool, calcification or hemorrhage. In the last decades, magnetic resonance imaging (MRI) has emerged as an imaging modality that enables accurate quantification of the main components of the plaque. Size, shape and plaque constituents can be identified noninvasively [1, 2, 3]. Other MRI techniques like phase-contrast have also been developed to acquire multidirectional blood velocity data in-vivo. 2D and 3D phase-contrast MRI has been used for the characterization of normal and pathological velocity profiles in those areas [4].

To study the dynamics of the flow in the cardiovascular system, the simulation tool has been proved to be a powerful complement. It has helped to investigate the problem through simple and complex geometry models, most of them based on in-vivo measurements [5, 6]. Particularly, image-based computational modeling can provide valuable information of the hemodynamical conditions and can assist the prediction of possible outcomes.

The present work aims to bring imaging and simulation closer in a robust framework. In this work, 3D MRI data of human carotids is acquired at Mount Sinai Hospital of New York. For each case, the geometries of the lumen and the vessel wall are segmented from images and converted into a computational mesh ready to run the simulations. Velocity measurements are also acquired and included as initial conditions in the computational model. As a first approach, only fluid simulations are performed. Once the framework will be validated, it will be extended to FSI to obtain an accurate simulation of the phenomenon occurring between the wall and the blood flow, to study the effect of the atherosclerotic plaque in the carotids.

METHODOLOGY

The problem is divided in three different parts:

1. MRI acquisition. Following the study protocols, patients are imaged on a Siemens MR/PET (3T) mMR. The imaging protocol is defined as follows: (i) the bilateral carotid arteries extending 3 cm below and above the carotid bifurcations are imaged using an 8-channel carotid coil. (ii) To delineate the vessel lumen, localization with gradient echo sequences, time-of-flight (TOF) images are acquired. (iii) To obtain black blood images and measure carotid stenosis, 3D SPACE with T2 weighting are acquired in free breathing conditions, untriggered with fat suppression.

As a result, 2D images in the coronal planes are obtained. Each slice has an in-plane resolution of 0.7x0.7 mm2, with an slice thickness of 0.7 mm. The flow in a vessel section is measured with a 2D, single-slice, cardiac-gated phase contrast sequence with through-plane velocity encoding (Venc=100cm/s). The acquisition plane is placed perpendicular to the carotid artery, 2 cm before the bifurcation, using a 3D time of flight acquisition to localize the vessels. The slice has the same resolution as the previous imaging protocol.

2. Image analysis and mesh generation. The geometry of the carotids is extracted from the MRI raw data performing a manual segmentation in ITK-SNAP [7]. The vessel wall is reconstructed computationally using the information in three different planes in space. In case of plaque, the corresponding materials are also identified. Once the segmentation is finished, the software generates the surface mesh of the lumen and the vessel wall in the STL (STereoLithography) file format. Finally, the mesh generator Iris, developed and supported at Barcelona Supercomputing Center (BSC), creates the unstructured finite element meshes for both fluid and solid geometries (Fig. 1).

3. Simulation. The appropriate framework for the simulation of fluid-structure interaction (FSI) in blood vessels is the arbitrary Lagrangian-Eulerian (ALE) description of continuous media. In this description, the fluid and solid domains are allowed to move to follow the distensible vessels and deforming fluid domain [8]. In this preliminary work, only

fluid simulations are presented. In this case, the fluid is simulated as laminar, viscous, incompressible, Newtonian flow in a fixed domain solving the Navier-Stokes equations and choosing suitable initial and boundary conditions [5]. The 3D computational model is performed in Alya, the multi-physics and parallel code developed at BSC [9, 10, 11, 12, 13] and solved in parallel in the Spanish Marenostrum supercomputer.

Fig. 1. Computational mesh created for a healthy case. Left: meshes of the the lumen (grey) and the vessel wall (red), composed of tetrahedral elements. Right: view of the bifurcation in the carotids.

Fig. 2 shows a pathological carotid artery where different components have been identified. The result of the simulation is presented in Fig. 3 and it is compared to the healthy carotid artery of the same patient. In both cases, MRI data has been used to provide the geometry and boundary conditions (i.e. inflow, and outflow) for a computational fluid dynamics calculation.

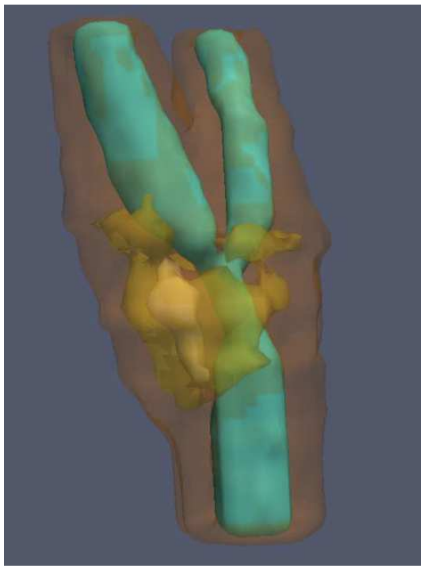

Fig. 2. Surface mesh of a pathologic case in the carotids bifurcation. Lumen (blue) and wall (brown) are represented in colors. The atherosclerotic plaque is drawn in yellow.

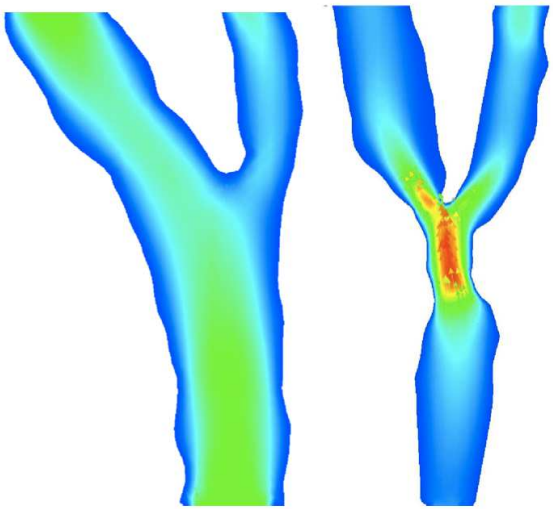

Fig. 3. The image-based computational framework is used to solve the hemodynamics of the problem. We compare the dynamics of the fluid in healthy and pathological arteries. Colors represent velocities. Right: healthy case. The velocity profile is normal, achieving a maximum of 70 cm/s at the systolic peak (PSV). Left: pathologic case. Maximum velocities are found in the bifurcation. Values are high is this case, achieving 200 cm/s at PSV.

VII. FUTURE WORK

Nowadays, theres a lack of realistic geometries used in numerical simulation. The pipeline presented here will constitute an efficient bridge to connect image and simulation. Given the increasing resolution and accuracy of information obtained from clinical imaging, the simulation tool is the complement that can provide an efficient way of research, prior to clinical trials which are expensive and can be a risk to the patients. Simulations can be performed on a patent's data and the results can be delivered to the doctor in an ad-hoc visualization manner (virtual lab) to get a deeper insight of the problem.

To identify the wall shear stress in the atherosclerotic material, flow will be simulated on a moving mesh using an (ALE) strategy. The artery wall and the plaque components will be modeled hyperelastic, isotropic, incompressible and homogeneous. The coupled FSI model will be solved in parallel in Marenostrum.

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REFERENCES

[1] Z. A. Fayad, J. T. Fallon, M. Shinnar, S. Wehrli, H. M. Dansky, M. Poon,

J. J. Badimon, S. A. Charlton, E. A. Fisher, J. L. Breslow, and V. Fuster, “Noninvasive In vivo high- resolution magnetic resonance imaging of atherosclerotic lesions in genetically engineered mice,” Circulation, vol. 98, no. 15, pp. 1541–1547, 1998.

[2] C. Yuan, W. S. Kerwin, M. S. Ferguson, N. Polissar, S. Zhang, J. Cai, and T. S. Hatsukami, “Contrast-enhanced high resolution MRI for atherosclerotic carotid artery tissue characterization,” J Magn Reson Imaging, vol. 15, no. 1, pp. 62–67, 2002.

[3] D. Tang, C. Yang, J. Zheng, P. K. Woodard, G. A. Sicard, J. E. Saffitz, and C. Yuan, “3D MRI- based multicomponent FSI models for atherosclerotic plaques,” Ann Biomed Eng, vol. 32, no. 7, pp. 947–960, 2004.

[4] M. D. Hope, D. D. Purcell, T. A. Hope, C. von Morze, D. B. Vigneron, M. T. Alley, and W. P. Dillon, “Complete intracranial arterial and venous blood flow evaluation with 4D flow MR imaging,” AJNR Am J Neuroradiol, vol. 30, no. 2, pp. 362–366, 2009.

[5] C. A. Taylor, T. J. Hughes, and C. K. Zarins, “Finite element modeling of three-dimensional pulsatile flow in the abdominal aorta: relevance to atherosclerosis,” Ann Biomed Eng, vol. 26, no. 6, pp. 975–987, 1998.

[6] C.A. Taylor and C.A. Figueroa, “Patient-specific modeling of cardiovascular mechanics, ”Annu Rev Biomed Eng, vol. 11, pp. 109–134, 2009.

[7] P. A. Yushkevich, J. Piven, H. Cody Hazlett, R. Gimpel Smith, S. Ho, J. C. Gee, and G. Gerig, “User-guided 3D active contour segmentation of anatomical structures: Significantly improved efficiency and reliability,” Neuroimage, vol. 31, no. 3, pp. 1116–1128, 2006.

[8] T. J. Hughes, W. K. Liu, and T. K. Zimmermann, “Lagrangian-eulerian finite element formulation for incompressible viscous flows,” Computer Methods in Applied Mechanics and Engineering, vol. 29, no. 3, pp. 329 – 349, 1981.

[9] G. Houzeaux, M. Vázquez, R.Aubry, and J. Cela.,“A massively parallel fractional step solver for incompressible flows,” Journal of Computational Physics, vol. 228, 2009.

[10] G. Houzeaux, M. Vázquez, X. Sáez, and J. Cela, “Hybrid mpi-openmp performance in massively parallel computational fluid dynamics,” Parallel Computational Fluid Dynamics, vol. 74, 2011.

[11] M. Vázquez, G. Houzeaux, S. Koric, A. Artigues, J.Aguado-Sierra, R.Arís, D. Mira, H. Calmet, H. O. F. Cucchietti, A. Taha, and J. Cela, “Alya: Towards exascale for engineering simulation codes,” in SIAM Journal on Scientific Computing. Also as preprint in arXiv:1404.4881, 2014.

[12] M. Vázquez, R. Arís, J. Aguado-Sierra, G. Houzeaux, A. Santiago, M. López, P. Córdoba, M. Rivero, and J. Cajas, “Alya red ccm: Hpc-based cardiac computational modeling,” Selected Topics of Computational and Experimental Fluid Mechanics, 2015.

[13] J. R. Cebral, M. Vázquez, D. M. Sforza, G. Houzeaux, S. Tateshima, E. Scrivano, C. Bleise, P. Lylyk, and C. M. Putman, “Analysis of hemodynamics and wall mechanics at sites of cerebral aneurysm rupture,” J Neurointerv Surg, 2014.