Asociación Argentina
de Mecánica Computacional

Mecánica Computacional Vol XXXVII, págs. 1609-1614 (artículo completo)
A. Cardona, L. Garelli, J.M. Gimenez, P.A. Kler, S. Márquez Damián, M.A. Storti (Eds.)
Santa Fe, 5-7 Noviembre 2019

STENTING AS HETEROGENEOUS POROUS MEDIA

Nicolás I. Dazeo, Javier A. Dottori, Gustavo A. Boroni and Ignacio Larrabide

Pladema, Universidad Nacional del Centro de la Provincia de Buenos Aires, Pinto 399, 7000 Tandil, Argentina, ndazeo@pladema.exa.unicen.edu.ar, http://www.pladema.net

Keywords: Intracranial Aneurysm, Flow Diverter Stent CFD, Heterogeneous Porous Media,

Abstract. An intracranial aneurysm is an abnormal dilation of a cerebral artery or vein caused by a weakness of the vessel wall and the blood flow. This dilatations are treated by changing local haemodynamics to reduce flow, reducing stress at the walls and causing a thrombosis. Flow diverter stents are endovascular devices placed in the parent blood vessel to divert blood flow away from the aneurysm itself (Pierot L., J Neurorad, 38(1):40–46 (2011)). Computational fluid dynamics is a non invasive method to study flow diverters and its influence in local haemodynamics. There are many methods in literature representing stents as homogeneous porous media. However, deployed stents change its shape heterogeneously according to vessel geometry. The shape deformation cause a variation in porosity and permeability across the device (Dazeo N. et al., Int J Num Meth Biomed Eng, 34(12):e3145 (2018).). In this work, porous medium methods are adapted to take local properties and create a heterogeneous medium. The methods are then compared qualitatively and quantitatively.

1 INTRODUCTION

Intracranial aneurysm are localised balloon like malformations in weakened vessel walls. This malformations can break and lead to haemorrhages and strokes.

Aneurysm can be treated with different endovascular devices. One of this devices is the flow diverter (FD) stent, a braided mesh deployed in the parent vessel to reduce velocity and pressure inside the aneurysm sac reducing the rupture risk. As different devices deployed in different positions can lead to different outcomes, treatment planing methods are needed.

Computational Fluid Dynamics (CFD) is commonly used to predict an endovascular intervention simulating FD haemodynamic effects. To model a FD in CFD, it's walls are defined in the simulation mesh as a no-slip boundary condition. As space between FD wires are 2 orders of magnitude smaller than vessel lumen, the mesh must be more refined in that region. Due to the high computational cost of simulating a mesh with a large ammount of elements, and FD intrinsic properties, this stents are usually modeled as Porous Media (PM) (Augsburger et al., 2011; Morales and Bonnefous, 2014; Raschi et al., 2014). Therefore, PM methods proposed in literature estimates a couple of coefficients to use the Darcy-Forchheimer law. While those coefficients are used to model the whole braided mesh, this is not homogeneous. Angles between braided mesh wires change locally because of the vessel geometry and the way the specialist deploys the stent (Dazeo et al., 2018).

Yadollahi-Farsani et al. (2019) proposes a PM method based on the occupied volume factor and wetted surface of each cell of a finite volume mesh. This method is limited to Finite Volume Methods. Also, if a flexible vessel wall is intended, it would require deformable mesh which could lead to further complications.

Some authors implemented methods for PM coefficient estimation equations from the average of braided mesh local properties. Because of this, same equations can be calculated locally. Therefore, this work proposes to use local properties to model the PM as a heterogeneous region. Then, results are compared to the no-slip Boundary Condition Method (BCM).

2 MATERIALS AND METHODS

2.1 Geometries

To study the impact of choosing a heterogeneous PM to model FD stents real geometries are used. 14 patients with intracranial aneurysms of different shapes, sizes, and locations are chosen for the study. On each patient, a FD stent was virtually deployed.

2.2 Simulations

The open source Finite Volume toolkit OpenFOAM in it's version 4.1 was used. In this case, a steady state solver was implemented based on the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm. A Darcy-Fochheimer source term based on porosity coefficient fields is added to the equations.

Blood is assumed as newtonian based on the study of Morales et al. (2013). Kinematic viscosity was set for human blood as $\nu = 3.774\text{x}10^{-06}\ m^2/s$.

The inlet was set to a fixed flow rate specific for each patient based on Reneman et al. (2006) analysis. At the outlets, pressure was set to $0\ Pa$.

Unstructured volumetric meshes were created with snappyHexMesh tool. BCM meshes have $7.3\text{x}10^6$ average number of elements , while untreated case and porous methods have $1.8\text{x}10^6$.

A mesh with double number of elements was made for each patient. All methods were then

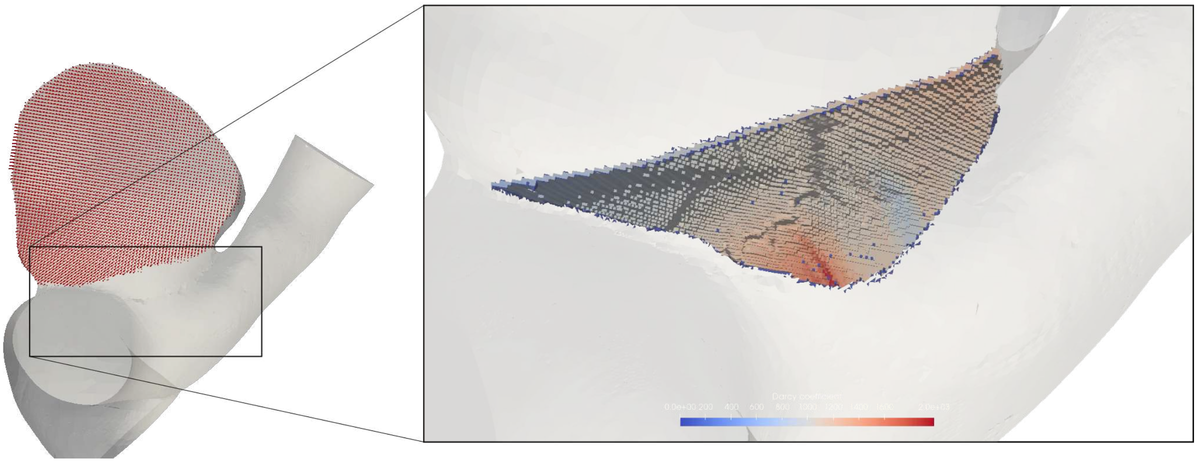

Figure 1: Uniform distributed cloud of points in the aneurysm sac and neck cells with non-zero porous media field.

simulated on the refined meshes and its variables compared to those obtained from the coarse one. There was a mean percentage error of $\%0.93$ and a standard deviation of $\%0.77$.

2.3 PM Methods

To estimate Darcy-Fochheimer coefficients, two methods are selected from literature: Morales and Bonnefous (2014)(M1) and Raschi et al. (2014) (R1) uses average porosity an permeability. Those properties can be acquired at each rhombus created by struts intersection. Therefore, heterogeneous versions of M1 and R1 (M2 and R2) are implemented with same equations as original methods, but evaluated at each rhombus. Those values are then linear interpolated on the PM region.

2.4 Measurements

To compare simulation results between methods, velocity is probed at a uniform distributed cloud of points in the aneurysm sac (Figure 1). Those probes are classified by their position. To achieve this, points are ordered by the distance to the aneurysm neck center and the distance to the wall, and then split into groups. From the distance to the aneurysm neck center, 3 groups of same size are obtained: The first group is near the neck, the second is at the center of the sac, and the third at the dome. Also, from the distance to the wall, points are divided in two groups: A quarter closer to the wall, and three quarters in the core.

The main purpose of using PM to model FD stents, is reducing computational loads and required time to get results. For this reason, meshing and simulating times are measured for each experiment.

3 RESULTS

3.1 Time

The computational time expended by simulated methods are shown in Figure 2. All PM methods shows similar times, while BCM takes times between x4.27 to x6.43 compared to others. There is no visible difference between heterogeneous and homogeneous methods.

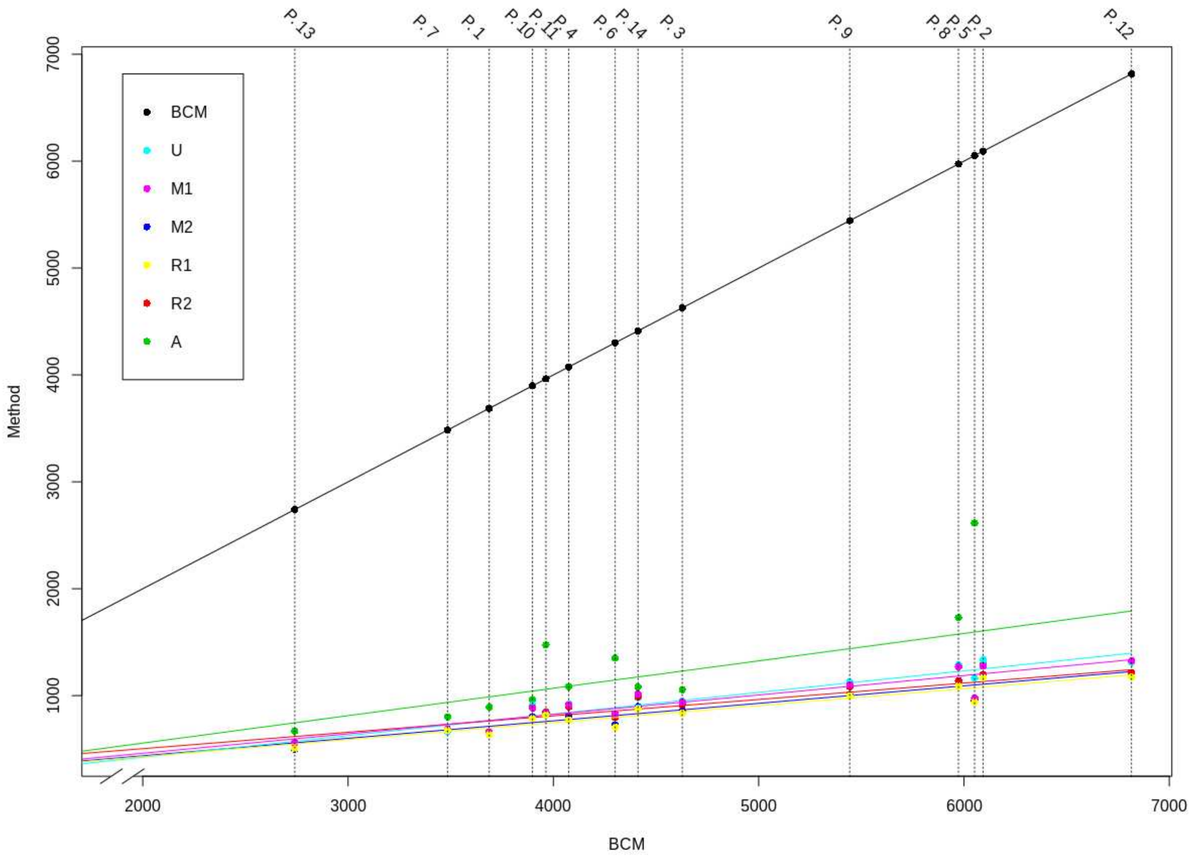

Figure 2: Time expended by meshing and simulation by each method (vertical axis) versus time expended by BCM (horizontal axis). Lines shows the linear fit between points for each method.

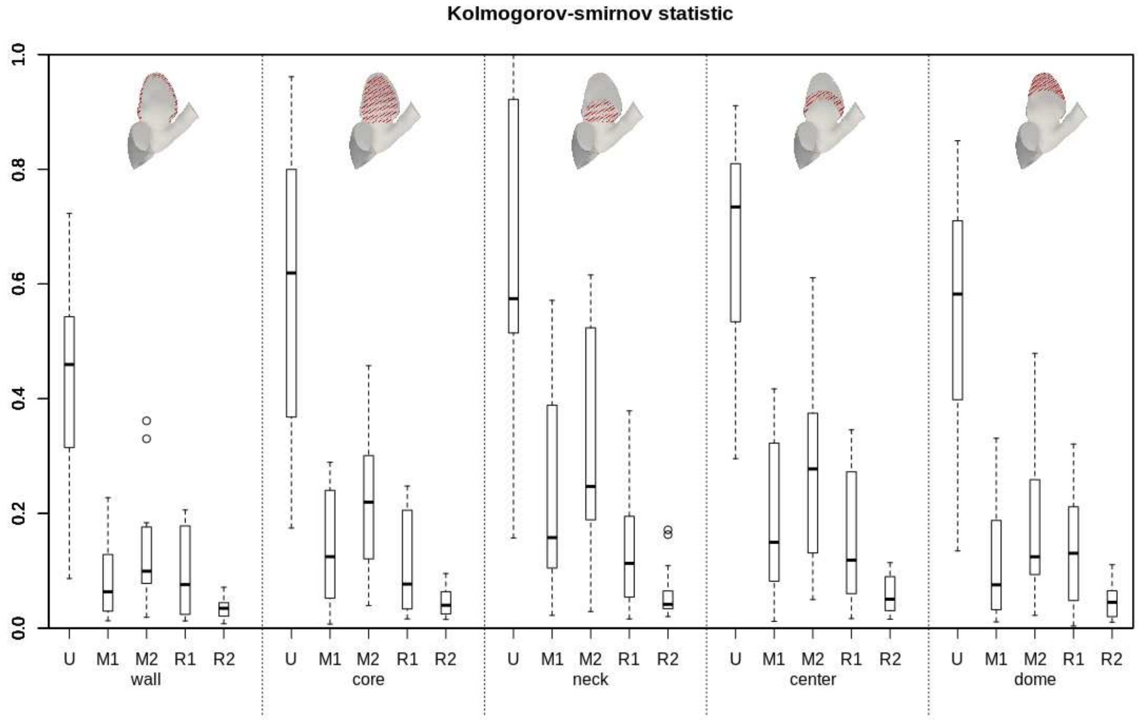

Figure 3: Kolmogorov Smirnov statistic between each PM method and BCM, segmented by aneurysm regions

3.2 Values

To compare velocity distributions quantitatively, the non-parametric test of Kolmogorov-Smirnov (K-S) was applied by groups. Figure 3 shows K-S statistic's for each group and method. The velocities probed on the untreated case is significantly more different than those probed on PM methods. Also, methods based on Raschi et al. (R1 and R2), are statistically closer to the BCM than Morales et al. (M1 and M2) methods. The heterogeneous technique applied on R2 improve the results versus R1, but the opposite happens with M2 versus M1, were M1 is closer to BCM than M2.

4 CONCLUSIONS

PM technique is a feasible method to model FD with reduced computational cost. Velocity distributions were statistically compared between different PM methods and the untreated case against the gold standard, BCM. The statistical analysis shows PM methods are significantly similar to BCM than the untreated case as it was expected.

There is still no a certain coefficient selection method to model FD as PM. Two methods where selected from literature to be analysed. The one proposed by Raschi et al. (2014) shows better results than Morales and Bonnefous (2014) in the selected geometries. Heterogeneous variants were evaluated for the two methods, were Raschi's was improved and Morales's deteriorated.

In the presented work, aneurysm sac velocity distributions caused by different PM methods for real geometries were analysed statistically. Likewise, other flow variables as pressure and vorticity can be chosen. Also, this analysis can be extended to other PM methods to get a better understanding of PM modelling.

ACKNOWLEDGEMENTS

This project is partly funded by PICT Start-up 2015-0006 and PICT 2016-0116 - FONCYT - ANPCYT of Argentina. N.D. is supported by CONICET PhD grant. The Titan Xp used for this research was donated by the NVIDIA Corporation. The financial support of these institutions is greatly appreciated.

REFERENCES

Augsburger L., Reymond P., Rufenacht D., and Stergiopulos N. Intracranial stents being modeled as a porous medium: flow simulation in stented cerebral aneurysms. *Annals of biomedical engineering*, 39(2):850–863, 2011.

Dazeo N., Dottori J., Boroni G., and Larrabide I. A comparative study of porous medium cfd models for flow diverter stents: Advantages and shortcomings. *International journal for numerical methods in biomedical engineering*, 34(12):e3145, 2018.

Morales H.G. and Bonnefous O. Modeling hemodynamics after flow diverter with a porous medium. In *2014 IEEE 11th International Symposium on Biomedical Imaging (ISBI)*, pages 1324–1327. IEEE, 2014.

Morales H.G., Larrabide I., Geers A.J., Aguilar M.L., and Frangi A.F. Newtonian and non-newtonian blood flow in coiled cerebral aneurysms. *Journal of biomechanics*, 46(13):2158–2164, 2013.

Raschi M., Mut F., Löhner R., and Cebral J. Strategy for modeling flow diverters in cerebral aneurysms as a porous medium. *International journal for numerical methods in biomedical engineering*, 30(9):909–925, 2014.

Reneman R.S., Arts T., and Hoeks A.P. Wall shear stress–an important determinant of endothelial cell function and structure–in the arterial system in vivo. *Journal of vascular research*, 43(3):251–269, 2006.

Yadollahi-Farsani H., Scougal E., Herrmann M., Wei W., Frakes D., and Chong B. Numerical study of hemodynamics in brain aneurysms treated with flow diverter stents using porous medium theory. *Computer methods in biomechanics and biomedical engineering*, pages 1–11, 2019.