Numerical study of a simplified cerebral aneurysm using a two different flow diverter stent modeling

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***Abstract*— The effectiveness of clinical treatments in-stent modeling have been recently started to be analyzed using Computational Fluid Dynamics (CFD) technique. Particularly, variation of pressure loss with flow velocity is used to evaluate permeability and internal resistance coefficients of the flow diverter stents to describe the stent properties to CFD model. The velocity profile is described as pulsatile parabolic at the inlet, the pressure is described at the outlet to be 93 mmHg as a mean arterial pressure (MAP) in the present study. The results implied that there was no significant difference found between porous media and stent implantation of a flow diverter stent modelings based on the studied cases. However, fluid flow simulations indicated that use of 48 wires stent allows more blood flow passing into the aneurysm sac compared to the 72 and 96 wires stents for the studied geometry. Effect of pressure change in the vessel and shape factor of the artery was neglected.**

Keywords: Cerebral aneurysm, flow diverter stent, porous media modeling

I. INTRODUCTION

An aneurysm formation is a phenomenon affecting many people in the world. It is actually sneaky phenomena with a low awareness by people. An aneurysm can initiate with a heartbeat when the blood vessel has any weakness at its structure. When this occurs in a brain artery, it causes being on tenterhooks for the patient. Besides, the cerebral aneurysm is actually relating to 5 percent of humanity [1], [2]. These cerebral aneurysms are generally treated with special stents called flow diverters.

Computational Fluid Dynamics (CFD) analysis type can be used to interpret for the effectiveness of the treatment [3], [4]; however, the most of the studies in the literature used porous medium modeling rather than real stent in their models without evaluating the difference between porous medium approach and stent implantation into the numerical models. Some of them used real stent deployment to increase the reality of the simulation by renouncing the consumed time for a solution [5], [6]. Others used the porous media insertion to the neck field by not knowing how much is realistic [7].

In the literature, most of the studies dealing with the blood flow in an aneurysm sac use a porous medium to model a flow diverter stent. In that case, permeability value determined for that flow diverter play a very important role since any variation in permeability can allow more or less blood flow into the aneurysm sac. Therefore, the use of correct value for the permeability of a flow diverter can give very promising results when compared with real stent placed models. As a result, this study focuses on the behavior of the blood in the artery with porous medium and stent modeling separately and provides a comparison between them. Besides, the present work discusses the fluid flow charateristics of flow diverter stents with 48, 72 and 96 wires.

II. MATERIALS & METHODS

A simplified geometry in Fig. 1 was constructed as two sections, which are aneurysm sac and artery. Artery diameter information was taken as 4 mm for 48, 72 and 96 wires flow diverter stents based on the stent brochure. The length of the artery was taken as 60 mm because the flow entering to sac and leaving from the sac should not be affected from the entrance or exit of the numerical model. After constructing the vessel, the dome of the aneurysm was built and adjusted as the diameter of 7 mm to be able to model blood flow inside a giant aneurysm when a flow diverter stent is placed at the aneurysm site by using a porous medium or a real stent. This measure is lower bound to have an operation for the aneurysm [8]. Briefly, the same geometry was used for all of the studies in the simulations. However, the flow diverter stent is modeled as a straight stent shape for three simulations while porous medium modeling is employed for the other three simulations at the neck of an aneurysm.

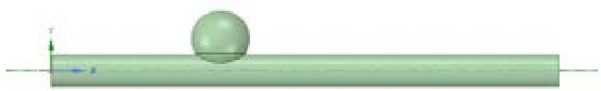


Fig. 1. The simplified geometry used in the simulations

A. *Momentum equations for porous medium*

Porous medium models for single-phase streams and multiphase flows are used by default in the superficial velocity porous formulation. ANSYS Fluent calculates superficial phase or mixture rates based on the volumetric flow rate in a porous region. The porous medium model is described in the following sections for single-phase flow.

The porous medium is modeled by adding a momentum source term to the standard fluid flow equations. The source term consists of two parts: a viscous loss term (Darcy, (first term on the right side of (1))) and an inertial loss term (second term to the right of (1)).

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|v|v_j\right) \quad \textbf{(1)}$$

Here "S_i", "i"(x, y or z) is the source term for the momentum equation, "v" is the magnitude of the velocity. "D" and "C" are the predicted matrices. This momentum equation contributes to the pressure gradient in the porous cell and generates a pressure drop in the cell which is proportional to the velocity of the fluid (or the square of the velocity).
For simple homogeneous porous media, the equation is used as follows;

$$S_i = -\left(\frac{\mu}{\alpha} v_i + C_2\frac{1}{2}\rho|v|v_i\right) \quad \textbf{(2)}$$

Here, α is permeability and C_2 is the internal resistance factor, μ is viscosity and ρ is density.

B. Derivation of porous coefficients based on experimental pressure and velocity data

When experimental data are available in the form of a pressure drop versus velocity across the porous medium, the coefficients for the porous medium can be determined to be placed into the numerical model. Unless experimental data are available, a CFD model with real stent properties can be created and the pressure drop and velocity data obtained as shown in Figure 2 can be used for the porous medium modeling [9]. The coefficients of the porous medium are determined as described below to provide a pressure drop in a porous medium of thickness Δn.

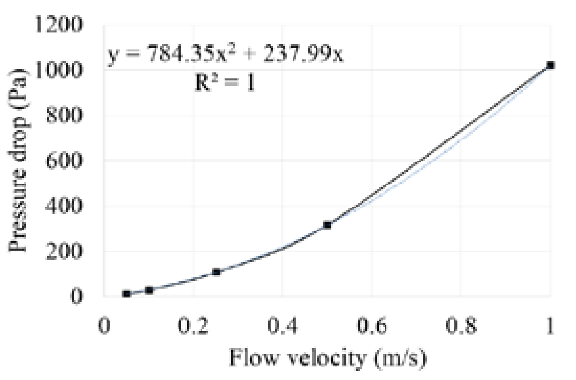


Fig. 2. Variation of pressure drop with flow velocity for 72 wires flow diverter

Pressure loss on each stent models was found and pressure drop vs. velocity graph is constructed according to TABLE 1. The trend line was drawn and the equation of the line was added into Figure 2. The trend line equation was obtained to be a second-order polynomial equation similar to equation (2). Permeability (α) and internal resistance factor (C_2) values of each stent were calculated and the results are given in Table 2 below.

TABLE 1. Properties belonging to fluid and perforated material

v (m/s)	μ (Pa.s)	ρ (kg/m³)	Δn (m)
0,05	0,0028873	1047,37	0,000032
0,1			
0,25			
0,5			
1			

TABLE 2. Permeability and internal resistance factor values for each stent used in simulations

	48W- 4MM	72W - 4MM	96W - 5MM
Permeability (m²)	3,52E-10	3,882E-10	2,837E-10
Internal Resistance Factor (m)	51729	46804	52377

C. Boundary conditions in simulations

In fluid specifications, blood was defined as a non-newtonian type fluid with Bird-Carreau [10]–[12] viscosity model. Blood molar mass and density was set as 64458 g/mol [13] and 1060 kg/m³ [12], [14], respectively. Inlet velocity profile was defined as pulsatile and parabolic. Besides, the velocity at the centerline of the artery was changed periodically between 0 and 0.625 m/s. At the wall, velocity is always zero because of the no-slip condition. As outlet condition, 93 mmHg opening pressure was defined, because ideal blood pressure is changing between 80-120 mmHg [15] and according to mean arterial pressure (MAP), the average pressure is 93 mmHg.

III. RESULTS

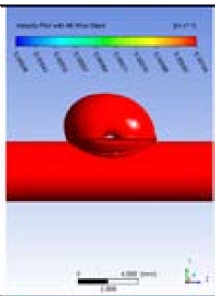
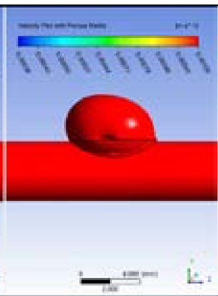
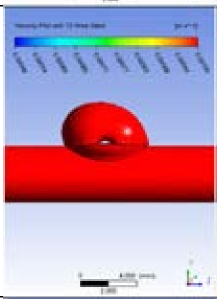
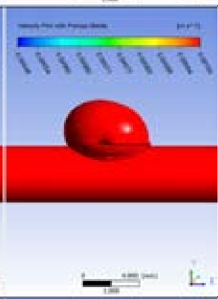
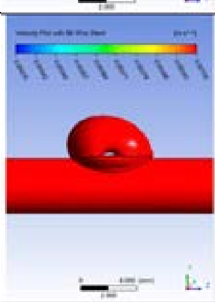
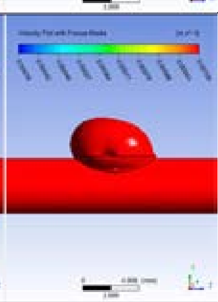
A. Difference between Implanting Stent and Porous Media on CFD

When blood enters the vessel with aneurysm, blood flow has a certain velocity due to its kinetic energy. If a stent is implanted into the aneurysm neck site, a significant amount of this kinetic energy would be absorbed in the stent while passing throughout the neck section of the aneurysm. As a result of the decreasing kinetic energy, the velocity of entering blood flow into the sac would decrease because of the porosity of the flow diverters.

In this study, there has not been observed any significant differences between the stent implantation and porous medium model results. As seen in Table 3, both simulations provided findings similar to each other in terms of the velocity of entering fluid to the sac at all wire options of the stent. Besides, all simulations results are shown for 0.4s because this time is the peak velocity moment for the velocity profile. Therefore, the greatest moment of entry into the aneurysm happened at this time. It is noted that simulations with stent have little bit larger contour compared to simulations with porous medium. This can be due to the porosity shape difference. The stent has pores which are similar to deltoid at the uniform sequence in every direction but the porous medium setup has uniform pores sequence and shapes.

When the number of the wire increases, amount of blood which is entering the aneurysm sac decreases as shown in Table 3. Therefore, the models with 48 wires have the same velocity value at the upper field of the aneurysm sac. As a result, the distance between the top of the iso-surface and stent or porous medium get smaller from 48 wires to 96 wires, and flow has more kinetic energy in the aneurysm field for the 48 wire flow diverter stent.

TABLE 3. Iso-surface results of three different stent wire and three different porous media on CFD

	Stent	Porous Media
48 Wires		
72 Wires		
96 Wires		

B. Difference between wire numbers

In Table 4, stent implantation was assumed to provide the most realistic values; therefore, porous medium results were compared with the flow diverter stent case in here. Percentage difference was calculated and the largest difference was found between 48 wires simulations with porous and stent cases. When the number of wire increases, the difference decreases as a percentage as shown in Figure 3 graphically. Table 4 is also provided in the present study to illustrate both midplane areas of the stents and the percentage difference between porous and stent for each wire number.

TABLE 4. Midplane areas and the percentage difference between porous and stent for each wire number

	Midplane Area (mm^2)	Difference (%)
48W Porous	16,5880	1,61
48W Stent	16,3255	
72W Porous	15,2649	0,97
72W Stent	15,4142	
96W Porous	14,8070	0,52
96W Stent	14,7309	

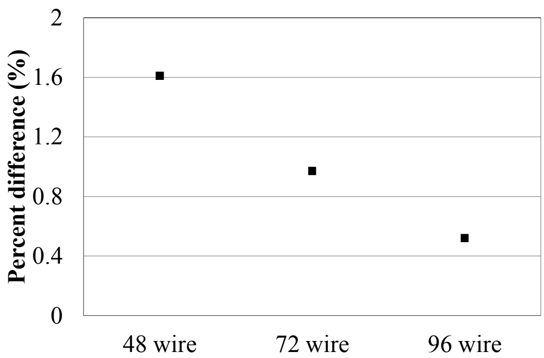


Fig. 3. Porous and stent difference at iso-surface mid-plane

IV. DISCUSSION

The findings of the study indicate that there is no remarkable difference between simulations with wire implanting stent and porous medium modeling. It is noted that the results of this work are restricted to only the simplified aneurismal model. Therefore, there is not any curve or convolution belonging to the artery. Thus, the artery shape factor was been neglected in this study. Another simplification is the constant pressure as outlet condition. In the real description, blood pressure is changing and this can affect the fluid flow characteristics of the blood flow at the aneurysm site.

As a conclusion, notwithstanding its limitation, this study does suggest that there is no significant difference between porous medium and stent implantation and porous medium modeling can be used with proper permeability and internal resistance coefficient values for CFD simulation of flow diverter stents. Furthermore, use of 48 wire flow diverter stent allows more blood flow into the aneurysm sac from parent artery compared to 72 and 96 wire flow diverter stents.

ACKNOWLEDGMENT

This work has been supported by TUBITAK (The Scientific and Technological Research Council of Turkey) under 1001 Program, Project #: 117M491.

REFERENCES

[1] O. Mutlu, A. B. Olcay, C. Bilgin, and B. Hakyemez, "Evaluating the Effectiveness of 2 Different Flow Diverter Stents Based on the Stagnation Region Formation in an Aneurysm Sac Using Lagrangian Coherent Structure," *World Neurosurg.*, pp. 1–11, 2019.

[2] B. Seibert, R. P. Tummala, R. Chow, A. Faridar, S. A. Mousavi, and A. A. Divani, "Intracranial aneurysms: Review of current treatment options and outcomes," *Front. Neurol.*, vol. JUL, no. July, pp. 1–11, 2011.

[3] M. Ohta, S. Wetzel, P. Dantan, C. Bachelet, K. O. Lovblad, H.Yilmaz, P. Flaud, D. A. Rüfenacht "Rheological changes after stenting of a cerebral aneurysm: A finite element modeling approach," *Cardiovasc. Intervent. Radiol.*, vol. 28, no. 6, pp. 768–772, 2005.

[4] B. M. Johnston, P. R. Johnston, S. Corney, and D. Kilpatrick, "Non-Newtonian blood flow in human right coronary arteries: Steady state simulations," *J. Biomech.*, vol. 37, no. 5, pp. 709–720, 2004.

[5] X. Wu., Z. Tian, J. Liu, W. Li, J. Chen, Y. Zhou, X. Yang, S. Mu "Hemodynamic impacts of flow diverter devices on the ophthalmic artery," *J. Transl. Med.*, vol. 17, no. 1, pp. 1–7, 2019.

[6] J. Zhong, Y. Long, H. Yan, Q. Meng, J. Zhao, Y. Zhang, X. Yang, H. Li "Fast Virtual Stenting with Active Contour Models in Intracranical Aneurysm," *Sci. Rep.*, vol. 6, no. February, pp. 1–9, 2016.

[7] Y. Li, M. Zhang, D. I. Verrelli, W. Yang, W. Chong, M. Ohta, Y. Qian "Modelling flow-diverting stent as porous medium with different permeabilities in the treatment of intracranial aneurysms : a comparison of a successfully treated case and an unsuccessful one."

[8] "Brain aneurysm - Treatment - NHS." [Online]. Available: https://www.nhs.uk/conditions/brain-aneurysm/treatment/. [Accessed: 22-Jun-2019].

[9] L. Augsburger, P. Reymond, D. A. Rufenacht, and N. Stergiopulos, "Intracranial stents being modeled as a porous medium: Flow simulation in stented cerebral aneurysms," *Ann. Biomed. Eng.*, vol. 39, no. 2, pp. 850–863, 2011.

[10] Y. I. Cho and K. R. Kensey, "Effects of the non-Newtonian viscosity of blood on flows in a diseased arterial vessel. Part 1: Steady flows," *Biorheology*, vol. 28, no. 3–4, pp. 241–262, 1991.

[11] S. N. Doost, L. Zhong, B. Su, and Y. S. Morsi, "The numerical analysis of non-Newtonian blood flow in human patient-specific left ventricle," *Comput. Methods Programs Biomed.*, vol. 127, pp. 232–247, 2016.

[12] S. Karimi, M. Dabagh, P. Vasava, M. Dadvar, B. Dabir, and P. Jalali, "Effect of rheological models on the hemodynamics within human aorta: CFD study on CT image-based geometry," *J. Nonnewton. Fluid Mech.*, vol. 207, pp. 42–52, 2014.

[13] D. C. F. Prof. Robert H. Hill, Jr., *Laboratory Safety for Chemistry Students*, Second. New Jersey: Wiley, 2016.

[14] S. O' Leary, "Predicting rupture of abdominal aortic aneurysms," *Eng. J.*, no. April, 2013.

[15] "What is blood pressure? - NHS." [Online]. Available: https://www.nhs.uk/common-health-questions/lifestyle/what-is-blood-pressure/. [Accessed: 23-Jun-2019].