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

†*Y. Li[1,2], M. Zhang[1,2], D. I. Verrelli[2], W. Yang[3], W. Chong[4], M. Ohta[5] and Y. Qian[2]

[1] Graduate School of Engineering, Tohoku University, Japan
[2] Faculty of Medicine and Health Sciences, Macquarie University, Australia
[3] Mineral Resources, CSIRO, Australia
[4] Neuroradiology Department, Monash Medical Centre, Australia
[5] Institute of Fluid Science, Tohoku University, Japan

* Presenting author: yujie.li@biofluid.ifs.tohoku.ac.jp
† Corresponding author: yujie.li@biofluid.ifs.tohoku.ac.jp

Abstract

Using a porous medium as a computational model for the real flow-diverting (FD) stent in computational fluid dynamics (CFD) improves the simulation efficiency. Adjustment of permeability level of the applied porous medium can result in various flow-resistance effects, which impact on the flow dynamics around and inside the aneurysm dome. Moreover, diversity in patient-specific aneurysm geometry also contributes to the difference in both the resistance force induced by the FD device and the aneurysmal haemodynamics. However, few studies have discussed the relationship between the setting of permeability and the intra-aneurysmal haemodynamics with different aneurysms.

In this study, in order to distinguish FD stents with different porosity, we simulated the porous medium stent with a range of permeabilities, respectively in a successfully treated aneurysm and an unsuccessfully treated one observed clinically. Haemodynamic parameters of intra-aneurysm mass flow rate (MFR) and energy loss (EL) were calculated to investigate their response to the alteration of permeability, as well as to the aneurysm morphology.

In comparison between the two patient-specific aneurysms, we found marked changes (70 and 40 % in MFR, 40 and 35 % in EL, respectively with successful and unsuccessful cases) in the aneurysmal haemodynamics as the porosity level of the implanted FD stents was increased by a factor of 25. The simulation results showed considerable differences in the relative flow-diversion between the clinically observed successful and unsuccessful case (up to 30 % in MFR and 45 % in EL). This study will help to provide future FD modellers with information about suitable selection of permeability level for different aneurysm cases.

Keywords: Permeability; Porous Medium; Computational Fluid Dynamics; Flow Diverting Stent; Cerebral Aneurysm

Introduction

Intracranial aneurysm (IA) is a vascular disease, observed by digital subtraction angiography (DSA) as a bulge that dilates out of the cerebrovascular wall. Untreated IAs may rupture, leading to subarachnoid haemorrhage, a severe condition that threatens the patient's life [1-3]. As an endovascular therapy, the flow-diverting (FD) stent is commonly used by neuroradiologists to keep most of the blood flow within the parent artery, thereby inducing blood clotting inside an aneurysm [4-5].

The flow-diversion efficacy of an implanted FD device is thought to be closely associated with the treatment outcome. To quantitatively analyse the flow-diversion efficacy, computational fluid dynamics (CFD) is frequently used to resolve the aneurysmal haemodynamics, as well as to quantify the haemodynamic alterations caused by different FD devices. Recently, an emerging technique that models an FD stent as a porous medium markedly decreased the computational time in CFD simulations [6]. By adjusting the permeability of the porous medium on the basis of the diversity in FD stent structures and porosity, the flow resistance induced by the porous medium stent model can be varied to represent different FD stents [6-8].

A problematic issue in FD treatment is that the outcomes may vary with respect to patients, *i.e.* a number of patients may still suffer from incomplete aneurysm occlusion even after two or three FDs were implanted. Previous studies suggest that the porosity of an FD stent can greatly affect the flow-diversion efficacy, thereby determining if an aneurysm can be completely occluded. However, the effects of device porosity on flow-diversion efficacy have not yet been quantitatively studied.

In this study, we aim to compare the flow-diversion efficacy of FD stents with different porosities, using permeability as a surrogate for porosity, and investigate the treatment outcomes of such devices in different patients, by contrasting the haemodynamic alterations in a successfully treated aneurysm and an unsuccessfully treated one.

Methods

Patient-specific Aneurysms

Two patient-specific intracranial aneurysm model geometries were studied, after we obtained the institutional ethics approvals. One of the aneurysms ('successful') was confirmed fully occluded 6 months after treatment, whereas the DSA of the other ('unsuccessful') revealed the existence of a residual aneurysm. A centre plane across the aneurysm lumen was selected to demonstrate and summarise the haemodynamic differences after FD treatments. The aneurysm geometries and the positions of the two planes are as shown in Figure 1.

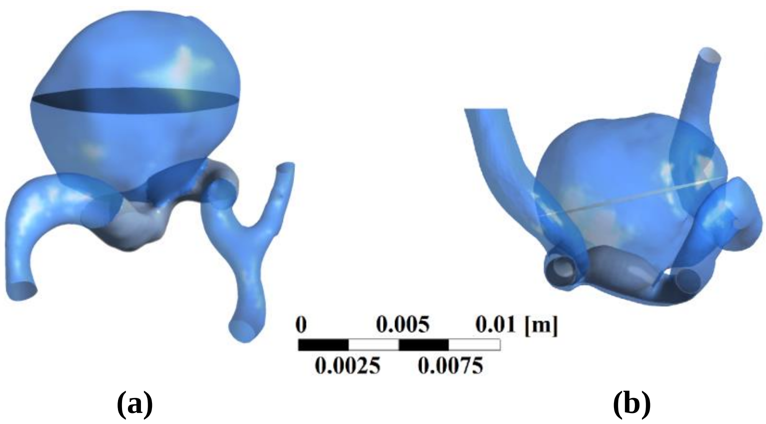

Figure 1. Geometries of two patient-specific aneurysms and the positions of the centre planes: (a) the successful aneurysm and (b) the unsuccessful aneurysm.

Flow-diverting Stent Modelling

The FD stent geometry was modelled as a fitted tube, with varied diameters, running through the parent artery that covers the aneurysm neck (see Fig. 1). Instead of the conventional stent geometry with individual FD wires, the FD stent was defined as a homogeneous porous medium tube in the simulation, with constant thickness of 100 μm. By defining the permeability, the resistance force induced by the porous medium can be adjusted, which is expressed as a momentum source term added to the standard fluid flow equation:

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

where α is the permeability, C_2 is the quadratic loss coefficient, i represents the x, y, or z coordinate, v is velocity, μ is viscosity, and ρ is density. The equation describing the correlation between the momentum source term and pressure drop is simplified as

$$\Delta p = -S_i \Delta e, \tag{2}$$

where Δe is the thickness of the porous medium [6].

Initial values of both permeability and inertial resistance factor were obtained based on a test model in numerical simulation that has a similar geometry to the *Silk* stent [6]. The permeability of an FD device is directly associated with the FD stent porosity. We adjusted the permeability by a series of factors — from 20% to 500% of the initial value (referred to as porosity level 20 to 500), to measure the effects of device porosity on the post-stenting haemodynamic alterations.

CFD simulation

The blood was assumed to be a Newtonian, incompressible fluid undergoing steady laminar flow. To match the properties of physiological blood flow, density and viscosity were specified as 1050 kg/m^3 and 0.0035 Pa·s, respectively. Mass flow rates of 250 mL/min at the inlet boundary were studied, while a 0 Pa static pressure was set at the outlets for all cases. A mesh dependency test was carried out before the simulation to ensure mesh quality and numerical accuracy. The fluid zone was discretised into 0.7 to 2.8 million elements with tetrahedral mesh elements, while denser mesh was added to the artery wall and stent surface. We used a commercial finite-volume-method based solver (CFX, Ansys, U.S.A.) to perform the CFD simulation.

Results

Figure 2 demonstrates the intra-aneurysmal haemodynamic result for the untreated condition and treated cases with the porosity level 20, 100, and 500. Figure 3 presents the alterations of flow-diversion efficacy, measured as intra-aneurysmal mass flow rate (MFR) and the Energy Loss (EL), at different levels of porosity.

We found that the velocity magnitude on the centre plane increases, when the device porosity increases. This trend is observed in both successful and unsuccessful aneurysms (Fig. 2).

By comparing the streamlines before and after FD treatments, an inflow reduction can be clearly observed in both aneurysms. With the successful aneurysm, the increasing porosity levels result in a decreasing blocking effect of aneurysmal inflow, while in the unsuccessful aneurysm, the flow-diversion effects remain similar from porosity level 20 to 500 (Fig. 2).

Visualisation of velocity iso-surfaces in both cases shows that a strong inflow jet exists in the unsuccessful case even under the condition of the lowest porosity level, whereas the inflow jet can be markedly reduced in the successful case when a FD stent is implanted (Fig. 2).

Quantitative results also show distinctions in the response to different porosity levels between the two aneurysms. For the successful case, the MFR drastically decreased from 80% to 16% when the porosity level was reduced from 500 to 20. For the unsuccessful case, however, the MFR only decreased to 40% when the porosity experienced the same reduction. Moreover, EL in the unsuccessful case reveals a 25–55% higher tendency than that of the successful case (Fig. 3).

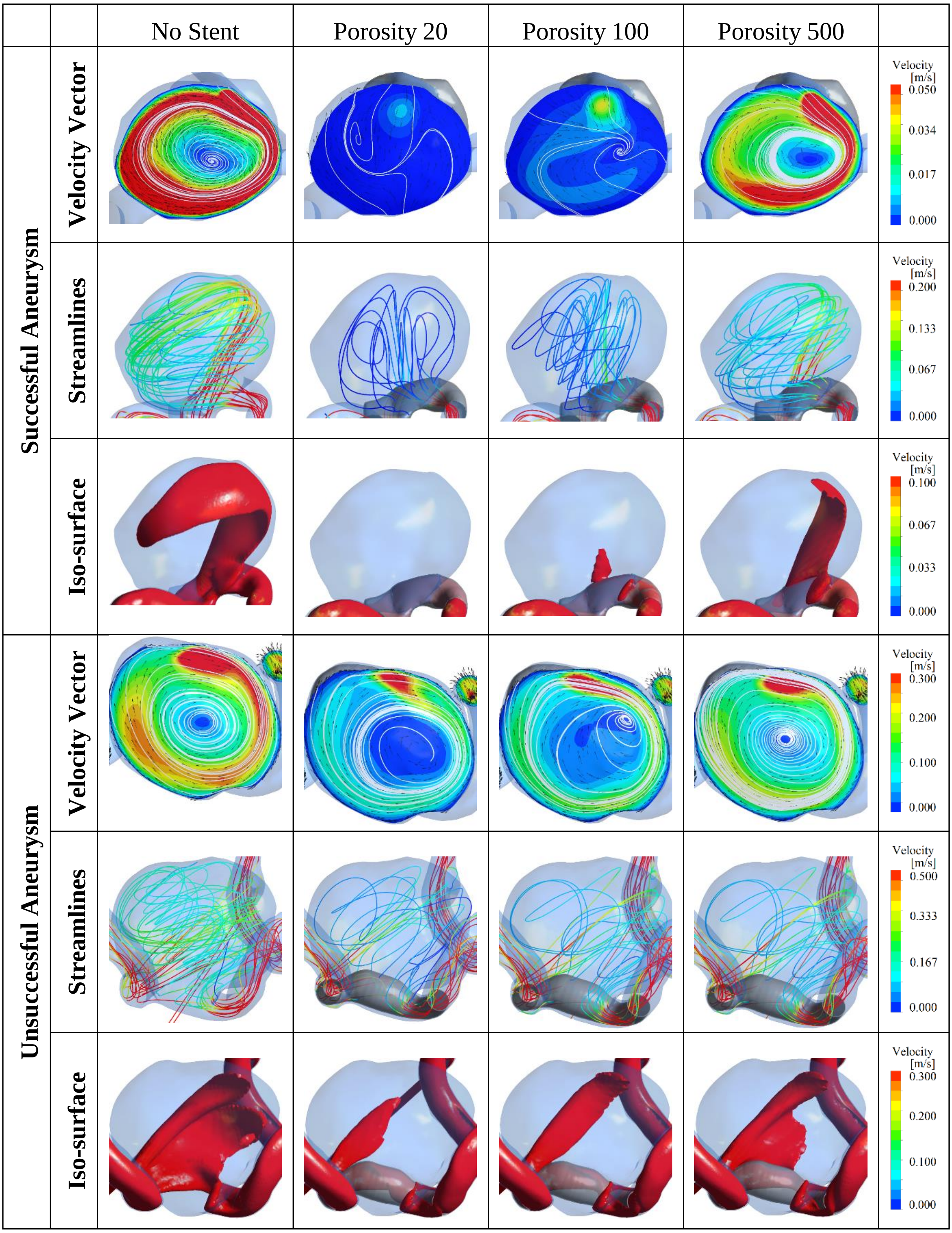

Figure 2. The velocity distributions on the centre plane, the streamlines and the velocity iso-surfaces for the successful and unsuccessful aneurysms, with a porous medium FD stent of various permeability levels, and the untreated cases.

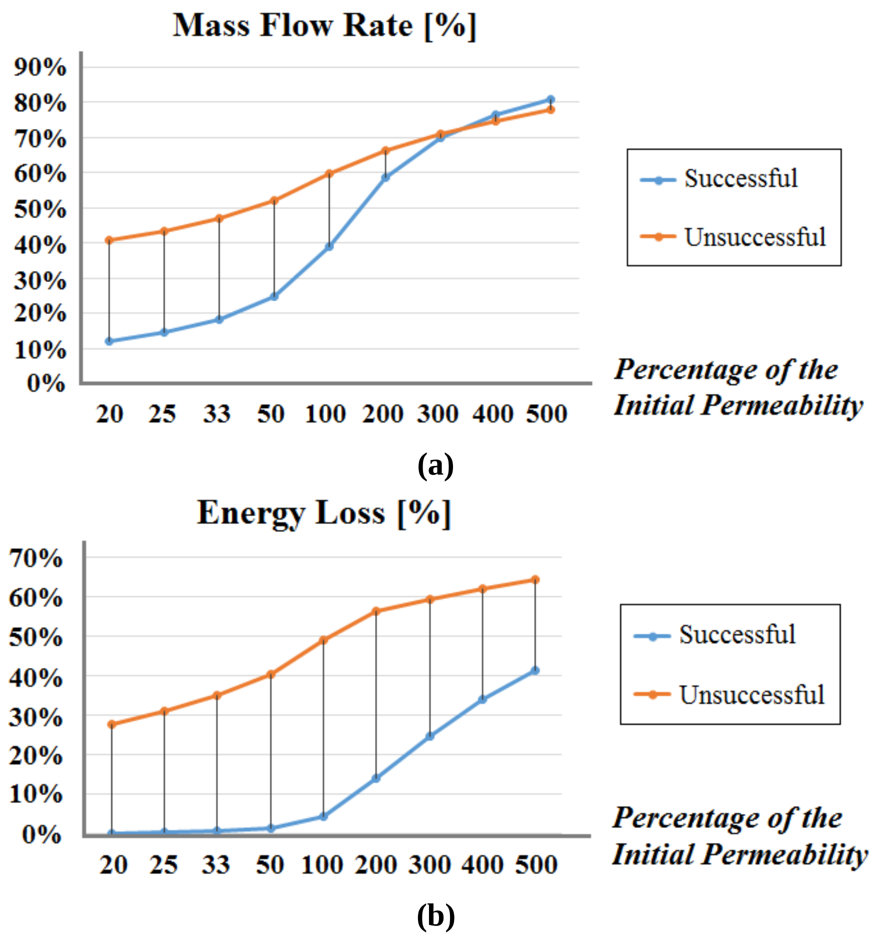

Figure 3. Comparison of aneurysmal haemodynamics between successful and unsuccessful aneurysms treated with a porous medium FD stent at a range of permeability levels: (a) Mass flow rate and (b) Energy loss.
(*Haemodynamic results are given as percentages of the respective untreated cases.*)

Discussion and conclusions

Techniques, such as stent compaction or multi-stent implantation [9-10] that decrease the porosity of the FD wires across the aneurysm ostium, can effectively improve the flow-diversion efficiency post-treatment. However, the highest level of flow diversion that can be achieved by decreasing the permeability level may differ across different aneurysm geometries, e.g. the successful case (16%) and the unsuccessful one (40%) in this study.

Furthermore, as can be seen in the unsuccessful case, a gap exists between the stent layer and the vascular wall, through which a strong inflow jet enters the aneurysm lumen. The DSA taken in the follow-up of the unsuccessful case also revealed the existence of the strong inflow jet. This suggests that not only the porosity level of an FD stent, but also the selection of device size in combination with parent artery morphology should be taken into consideration by neuroradiologists in the design of an FD stent treatment.

To sum up, we investigated the effect of device permeability levels on a successfully treated aneurysm and an unsuccessful one with an implanted FD stent. We found that decreasing the permeability of an FD stent can improve the flow-diversion efficacy post-treatment, but how much improvement can be achieved depends on the morphological characteristics of the aneurysm and parent artery, as well as the selection of device size.

Acknowledgements

This study was supported by the ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan), the Macquarie University Research Excellence Scholarship (iMQRES, No. 2015256), and Australian Research Council Linkage Projects (Grant ID: LP130100423).

References

[1] J. Cebral, E. Ollikainen, B. J. Chung, F. Mut, V. Sippola, B. R. Jahromi, R. Tulamo, J. Hernesniemi, M. Niemela, A. Robertson and J. Frosen. Flow conditions in the intracranial aneurysm lumen are associated with inflammation and degenerative changes of the aneurysm wall, *Am. J. Neuroradiol.*, vol. 38, no. 1, pp. 119–126, Jan. 2017.

[2] S. E. Francis, J. Tu, Y. Qian and A. P. Avolio. A combination of genetic, molecular and haemodynamic risk factors contributes to the formation, enlargement and rupture of brain aneurysms, *J. Clin. Neurosci.*, vol. 20, no. 7, pp. 912–918, Jul. 2013.

[3] M. D. Ford, H. N. Nikolov, J. S. Milner, S. P. Lownie, E. M. DeMont, W. K. F. Loth, D. W. Holdsworth and D. A. Steinman. PIV-measured versus CFD-predicted flow dynamics in anatomically realistic cerebral aneurysm models, *J. Biomech. Eng.*, vol. 130, no. 2, p. 21015, 2008.

[4] F. Mut, M. Raschi, E. Scrivano, C. Bleise, J. Chudyk, R. Ceratto, P. Lylyk and J. R. Cebral. Association between hemodynamic conditions and occlusion times after flow diversion in cerebral aneurysms, *J. NeuroInterventional Surg.*, vol. 7, no. 4, pp. 286–290, Apr. 2015.

[5] S. Fischer, M. A. Perez, W. Kurre, G. Albes, H. Bäzner and H. Henkes. Pipeline Embolization Device for the treatment of intra- and extracranial fusiform and dissecting aneurysms: initial experience and long-term follow-up, *Neurosurgery*, vol. 75, no. 4, pp. 364–374, Oct. 2014.

[6] 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, Feb. 2011.

[7] M. Ohta, H. Anzai, Y. Miura and T. Nakayama, Parametric study of porous media as substitutes for flow-diverter stent, *Biomater. Biomed. Eng.*, vol. 2, no. 2, pp. 111–125, Jun. 2015.

[8] M. Kim, D. B. Taulbee, M. Tremmel and H. Meng, Comparison of two stents in modifying cerebral aneurysm hemodynamics, *Ann. Biomed. Eng.*, vol. 36, no. 5, pp. 726–741, May 2008.

[9] J. Xiang, D. Ma, K. V. Snyder, E. I. Levy, A. H. Siddiqui and H. Meng. Increasing flow diversion for cerebral aneurysm treatment using a single flow diverter, *Neurosurgery*, vol. 75, no. 3, pp. 286–294, Sep. 2014.

[10] D. Ma, J. Xiang, H. Choi, T. M. Dumont, S. K. Natarajan, A. H. Siddiqui and H. Meng. Enhanced aneurysmal flow diversion using a dynamic push-pull technique: an experimental and modeling study, *Am. J. Neuroradiol.*, vol. 35, no. 9, pp. 1779–1785, Sep. 2014.