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# Homogeneous porous media to model the treatment of intracranial aneurysms with Flow Diverting Stents?

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## 1. Introduction

Intracranial aneurysms (IA) are a major cause of subarachnoid hemorrhage, with high mortality and morbidity. Endovascular treatment has become standard, with flow diverting stents (FDS) representing a major advance in minimally intrusive aneurysmal surgery. These high porosity tubular meshes are deployed in the parent vessel and treat by reducing the flow into the aneurysmal sac. This slower flow leads to the formation of a thrombus which, in successful treatment, fully occludes the sac and isolates the wall from mechanical stresses, preventing rupture. However, 20% of the aneurysm requires retreatment due to persistent blood flow inside the aneurysmal sac (Bender et al. 2018). Computational fluid dynamics (CFD) prediction of treatment failure would advance treatment planning and reduce reoperation. To reduce computational cost, the stent is commonly modeled as a homogeneous porous medium (Marsh et al. 2019; Li et al. 2021):

$$\Delta p = -(\mu \frac{1}{\alpha} v + C_2 \frac{1}{2} \rho v^2)$$

where $\Delta p$ is the pressure drop induced by the porous medium, $\mu$ and $\rho$ are blood viscosity and density, $v$ is velocity. The permeability $a$ and the inertial resistance $C_2$ depend on both stent and impinging flow characteristics (influenced by the parent vessel curvature) (Augsburger et al. 2011).

This CFD study aims at understanding the effect of the impinging flow angle on the porous medium parameters. Porous model results are compared to experimental results and stent-resolved CFD simulations for idealized IA (Barbour et al. 2021).

## 2. Methods

### 2.1 Porous model parameters

A stent geometry with 33 $\mu$m-diameter struts was implanted in a section of a straight tube (D=1mm) with varying angles relative to the inflow\ [90°,60°,40°,20°,10°]. 4 inlet velocities from 0.1 to 1m/s were set at the inlet.Pressures difference between upstream and downstream of the stent surface were computed ($\Delta p$).The normal component of velocity to the stent surface vnorm was extracted and plotted against $\Delta p$. Finally, a 2$^{nd}$ order polynomial was fit to derive $a$ and $C_2$.

### 2.2 CFD simulations

CFD simulations were implemented for 4 idealized IA geometries, with varying parent vessel curvature $\kappa$ (Barbour et al., 2021). For each geometry, 3 simulations were run: pre-treatment, treatment modeled with a porous media, and stent-resolved (Fig. 1(a)). The stent-resolved geometries were obtained from $\mu$ CT images of the stents deployed in silicon flow phantoms (Barbour et al., 2021).

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Unsteady simulations were implemented in Fluent (Ansys Inc, USA) with a time step of $5e^{-4}$ s for 2s. A Poiseuille velocity profile was applied at the inlet of the parent vessel, for 4 flow rates from 100 to 400 mL/min (Re = [144 – 576]).

### 2.3 Comparison to experimental data

Post-treatment velocity fields were compared to pre-treatment values to assess the effect of the treatment. For the stent-resolved configuration, 3D velocities in the midplane were also compared to previous PIV experiments (Barbour et al. 2021) for validation. A comparison between the porous media model and the stent-resolved model was performed to assess the performance of the porous medium model.

## 3. Results and discussion

The angle between the impinging flow and the stent surface had a limited impact on the relationship between $\Delta p$ and $v_{norm}$.The best fit values were $a$=5.33 . $10^{-10}$ $m^2$ and $C_2$=2.41 .104 $m^{-1}$.

The intra-aneurysmal flow topology was influenced by the curvature of the vessel and by the Re. For low Re and no curvature, the flow in the sac was attached to the flow in the parent vessel, while separation occurred for higher curvatures and higher Re (Fig. 1(b)). For both post-treatment models, the velocity in the IA sac was found to be proportional to the Re in the parent vessel. However, the porous medium model shows a stronger reduction of the velocity in the sac, thus overestimating the effect of the treatment. A sensitivity study was performed to quantify the effect of the variation of $a$ and $C_2$ on hemodynamics. Though a variation of alpha led to important changes in the velocity, a variation of $C_2$ had marginal impact, due to the relatively low velocities in the sac. Finally, using a combination of $a$ and $C_2$ resulting in the same average velocity in the sac for the porous model and for the stent-resolved, important differences in flow topologies were observed (Fig. 1(c)). For the stent resolved model, the flow enters the sac at the distal end, recirculates in the sac around the z axis and reattaches to the flow in the parent vessel at the proximal edge of the sac (Fig. 1(c) – right). For the porous medium model, the flow enters the sac through the entire midplane of the neck, recirculates along the walls moving away from the midplane, and exits the sac through the perimeter of the neck, reattaching to the parent vessel flow along the sidewalls (Fig. 1(c) – left).

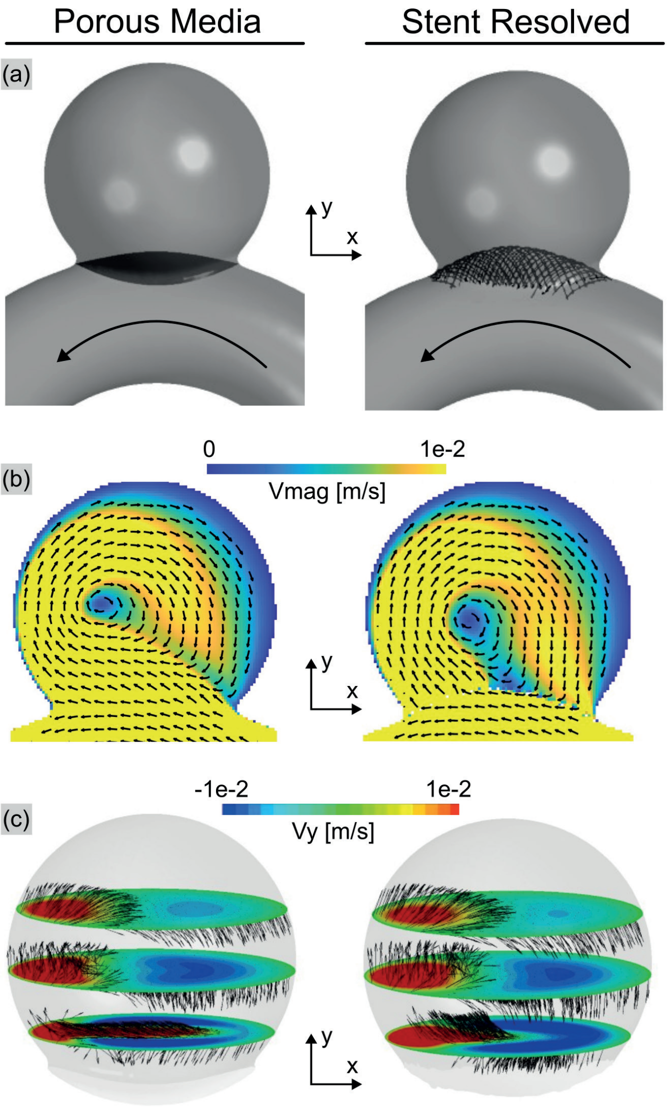

**Figure 1.** (a) Porous media and stent-resolved models for a curvature of the parent vessel κ=0.14$mm^{-1}$; (b) Velocity magnitude in the mid-plane (Re = 288); (c) Velocity fields in 3 sections in the aneurysmal sac (Re = 288).

## 4. Conclusions

This numerical study tests the accuracy of the porous medium to model the effect of the FDS on intra-aneurysmal hemodynamics. Though similar reduction in flow is achieved, the porous medium does not accurately replicate the flow patterns in the sac, suggesting the importance of stent structure to understand detailed post-treatment hemodynamics, necessary to understand and model thrombosis, and ultimately to predict the effect of endovascular treatment of IA.

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## Conflict of Interest Statement

None.

## Contributor Roles

FC: Conceptualization, Formal analysis, Methodology, Software, Resources, Supervision, Visualization, Writing-original draft; DMLA: Formal analysis, Methodology, Software, Writing-review & editing; MCB: Conceptualization, Methodology, Writing-review & editing; AA: Conceptualization, Methodology, Funding acquisition, Resources, Writing-review & editing.

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