MRI-BASED COMPUTATIONAL MODELING OF FLOW THROUGH A FLOW-DIVERTING STENT

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Introduction
Intracranial aneurysms unsuited for clipping or coiling (e.g. wide-neck aneurysms) may be treated by flow-diverting stents (FDS). These new generation devices differ from standard stents in that they have much finer and denser struts, thus ensuring some resistance to flow across the stent wall. The use of FDS aims at reconstructing the parent vessel geometry and reducing the flow into the aneurysmal part of the vessel thus causing thrombotic occlusion of the aneurysmal sac. Flow alterations caused by the FDS placement can be modeled with computational fluid dynamics (CFD). In this study of an FDS deployment in a silicon model of a giant ICA aneurysm we have used MR angiography as a basis for computational modeling and time-resolved phase-contrast MR velocimetry (4D MRV) for validation of CFD.

Methods
A giant ICA aneurysm considered for treatment by an FDS was imaged with MRA and the data were used to generate patient-specific geometry for both computational and in vitro models. A wax model was constructed on a 3D printer and embedded in a block of silicone (Fig. 1.a). The wax was then melted out thus leaving a channel corresponding to the lumen geometry of the aneurysmal ICA. The neuro-interventional team at our institution deployed an FDS in this flow phantom. After deployment, flow through the stented phantom was measured with 4D MRV. In addition, DSA cine images were acquired prior to and after the procedure, to examine filling of the aneurysmal volume with contrast. Numerical simulations of the preoperative and postoperative flow were carried out with a finite-volume solver, FLUENT. In order to conduct CFD simulations of the postoperative flow, the FDS was modeled as a thin porous tube connecting the inlet and outlet of the lesion. The viscous and inertial resistance of the porous media was prescribed using previously published parameters [1]. A post-processing technique referred to as "virtual ink" [2], based on numerical simulation of a passive scalar transport, was used to visualize the flow and asses the changes in flow residence time.

Results
Preoperative flow fields measured in vivo with 4D MRV and computed with CFD are shown in Fig.1 (b) and (c). In each approach the results showed a jet extending across the aneurysm with two counter-rotating vortices, one on each side. This confirmed that creating the silicone phantom from MRA data provided an accurate geometry. The flow following the FDS deployment measured in vitro with 4D MRV is shown in panel (d) and postoperative CFD results are shown in panel (e). The high-velocity jet through the aneurysm is eliminated as the flow is diverted by the FDS into the distal ICA. There is some residual flow across the porous wall of the device; however velocities in the aneurysmal volume are substantially reduced. There is very good qualitative agreement between CFD predictions of post-procedural flow and the 4D MRV measurements.

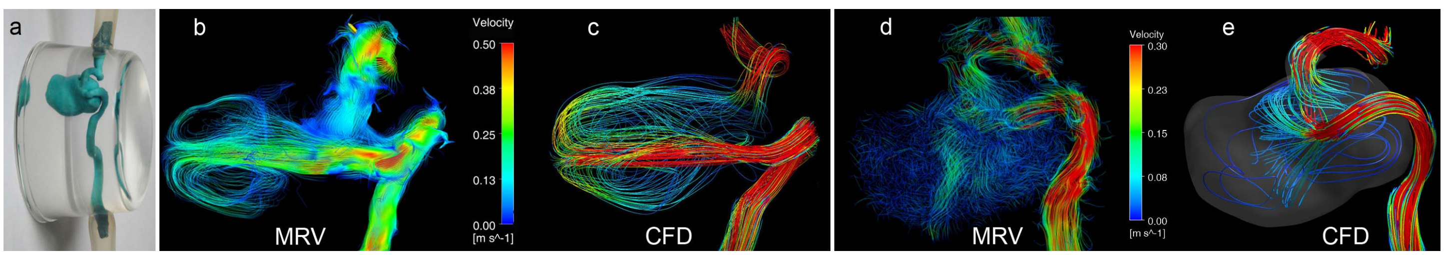

Figure 1 Flow in a giant ICA aneurysm model: (a) Wax model embedded in silicone. Preoperative streamlines obtained with (b) in vivo PC-MRI, (c) CFD. Streamlines following FDS deployment obtained with (d) in vitro PC-MRI, (e) CFD.

The DSA cine images acquired pre (Fig. 2.a) and post (Fig. 2.b) FDS deployment show the transport of contrast through the model. Numerical simulations of the virtual ink transport are shown in Fig. 2.c. The ink injection was simulated for a number of cardiac cycles and was followed by injection of ink-free fluid that continued until the ink was washed-out from the geometries. The images at the top (preoperative) and bottom (postoperative) of each column show the ink distribution at the same time following ink injection. In the preoperative case, the ink is carried by the jet across the lesion and quickly fills the aneurysmal volume. Following the FDS deployment, the ink seeps through the porous wall taking a substantially longer time to fill the aneurysm. There is a good qualitative agreement between the CFD predictions and the DSA images. The ink washout results show that the flow residence time in the distal part of the aneurysmal sac was substantially increased following the procedure: at the time when the preoperative model is empty, the postoperative model is still filled with ink. Previous studies have demonstrated that thrombus formation may be facilitated in regions of flow separation and increased residence time. Thus, the stagnant flow observed in the aneurysm following the FDS deployment is likely to induce thrombotic occlusion.

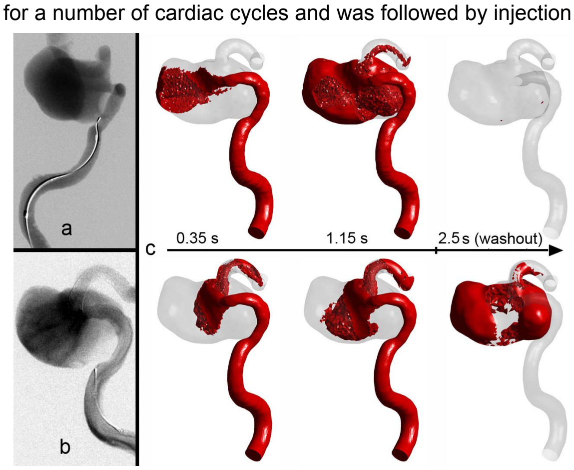

Figure 2 Contrast transport before and after FDS deployment: (a) DSA image of the contrast filling the distal part of the lesion; (b) DSA following the procedure; (c) CFD-predicted virtual ink distribution in preoperative (top) and postoperative (bottom) models.

Conclusions
The results indicate that CFD models constructed from MRI data can be used to predict the efficacy of FDS's and help in evaluating this therapy on a patient-specific basis.

References
1. *Augsburger et al., Intracranial Stents Being Modeled as a Porous Medium: Flow Simulation in Stented Cerebral Aneurysms. Ann Biomed Eng, 2011.*
2. *Rayz et al., Flow residence time and regions of intraluminal thrombus deposition in intracranial aneurysms. Ann Biomed Eng, 2010.*

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