ABSTRACT

A new realistic finite element method (FEM) based endovascular coil deployment technique was developed to explore the hemodynamic modifications of coiling in addition to flow diverter (FD) treatment. A patient-specific internal carotid artery aneurysm was used as a test case, and a single flow diverter was deployed using a previously developed method [1], along with several coils using the new method. Results showed fluctuations in hemodynamic parameters at low packing densities (1-3 coils) which are unexpected. At high packing density however (6 coils), results were consistent with expectations. These results suggest that adding coils at low packing densities to FD treatment may not cause significant additional flow reduction into the aneurysm sac, but may provide a scaffold for aneurysmal thrombus formation.

Keywords: aneurysm, hemodynamics, endovascular coils, flow diverter, computational fluid dynamics, finite element method

INTRODUCTION

Conventional endovascular techniques (embolic coiling), have been used for decades as a standard in treating intracranial aneurysms. Coils provide immediate protection to the aneurysm dome by triggering the formation of thrombus through additional bulk flow stasis in the aneurysm sac, providing a scaffold for the thrombus, and diffusing impinging jets which are considered dangerous for the aneurysm. The emergence of alternative endovascular paradigms such as flow diversion have given rise to new possibilities in aneurysm treatment. Flow diverters, such as the Pipeline Embolization Device (PED, Covidien, Irvine, CA) have been used recently to treat previously difficult-to-treat aneurysms. However, post-FD rupture complication was reported, especially for large aneurysms. Clinicians were suggested by the FD manufacturers that deploying sparse coiling in conjunction with the FD would improve clinical outcome. However, it is still unclear how the combination of these devices work better and affect post-treatment hemodynamics. To investigate this, we developed a new finite-element-method (FEM) based technique for virtual coil deployment, which captures their realistic mechanical interactions during deployment. Previous virtual coiling techniques have included path planning and space filling algorithms which artificially place the coils inside the aneurysm and may not accurately capture their true properties [2]. In conjunction with our previously developed realistic FEM based virtual deployment technique for FD, we applied our new coiling technique in a patient-specific aneurysm under 5 scenarios (a PED alone and a PED with 1, 2, 3, and 6 coils) to investigate the hemodynamic modifications by the coils in addition to FD.

METHODS

Aneurysm Geometry

One patient-specific aneurysm geometry (Figure 1) was virtually treated with a single PED and a PED with 1, 2, 3, and 6 coils.

FEM Modeling of PED and Coil Deployments

The PED was deployed using the previously developed high fidelity virtual stenting (HiFiVS) method [3]. Incorporating similar concepts from HiFiVS, our new technique for coil deployment also captures the realistic mechanical interactions between the coils themselves and the vessel wall, as opposed to artificially filling the aneurysm with coils. A “pre-shaped” coil geometry was adopted for this study, described previously [4]. The geometry was generated...
using an in-house MATLAB (MathWorks, Natwick, MA) script and imported into the FEM based software Abaqus/Explicit 6.12 (SIMULIA, Providence, RI). To simplify the deployment workflow (Figure 2), the aneurysm sac was isolated from the parent vessel. Under the assumptions of Euler-Bernoulli beam theory, the coils were deployed into the aneurysm sac via a catheter.

**CFD Modeling**

All CFD analysis was conducted using the finite-volume based software Star CCM+ v.8. The computational grids for each scenario were generated using the unstructured polyhedral meshing algorithm. The parent vessel inlet condition was adopted from literature. The incompressible Navier-Stokes equations were solved under the assumptions of steady-state, rigid wall, laminar and incompressible flow. Blood was treated as a Newtonian fluid with a density of 1056 kg/m³ and viscosity of 3.5 cP. The hemodynamic parameters examined include velocity vectors and streamlines, WSS distribution, and relative inflow rate.

**RESULTS and DISCUSSION**

Coil Deployment Results

A total of six coils plus one PED were deployed for the test case (Figure 3). The packing densities (percentage of the aneurysm sac volume occupied by coils) for the 1, 2, 3, and 6 coil scenarios were 3.7%, 7.4%, 11.1%, and 22.2% respectively.

**Hemodynamic Modifications after FD Deployment**

Velocity vectors (Figure 4) revealed that at low packing densities (1-3 coils), the impingement jet was not completely blocked by the coils. At high packing density (6 coils), the flow was almost entirely blocked from entering the aneurysm sac. The WSS distributions (Figure 5) revealed that the coils helped alleviate zones of high WSS in the aneurysm sac, though some zones of elevated WSS persisted. Quantification of average velocity, inflow rate, and average WSS revealed fluctuations in flow parameters at low packing densities (1-3 coils), which was inconsistent with the expected trend that an increase in the number of coils should have caused a decrease in intra-aneurysmal flow parameters. We believed that these fluctuations were due to the random distribution of coils in the aneurysm sac and the incomplete coverage of the aneurysm neck at low packing densities. It was also clear from the quantitative data the majority of flow reduction in the aneurysm sac was achieved by the PED alone and not the coils.

**CONCLUSIONS**

This study demonstrated that adding coils at low packing densities (e.g., 4-11%) to FD treatment would not generate additional massive aneurysmal flow reduction, while high packing coil density (>20%) generated significant flow blockage. We believed that sparse coils may provide a scaffold for aneurysmal thrombus formation to reduce post-FD rupture complication. In the future, more aneurysm geometries and different packing densities should be further investigated.

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**REFERENCES**


