Flow Diversion and Outcomes of Vertebral Fusiform Aneurysms After Stent-Only Treatment: A Hemodynamic Study

Wenqiang Li[1], Jian Liu[2], Yisen Zhang[2], Kun Wang[2], Zhongbin Tian[2], Qianqian Zhang[2], Chuhan Jiang[2], Xinjian Yang[2], Yang Wang[1]

■ BACKGROUND: **The aim of this study was to determine the effectiveness of treating vertebral fusiform aneurysms (VFAs) only with stents. Using computational fluid dynamics, we evaluated the hemodynamic patterns of VFAs after stent-only treatment (SOT) and monitored hemodynamic changes in the side branches.**

■ METHODS: **Between September 2014 and December 2015, we enrolled 10 consecutive patients with VFAs who underwent SOT. Successful aneurysm reconstruction is defined as perfect reconstruction of the parent artery and complete or nearly complete occlusion of the aneurysm. Otherwise, the reconstruction was considered unsuccessful. After SOT, we used computational fluid dynamics to assess hemodynamic changes in aneurysmal velocity, wall shear stress, and relative residual time (RRT) as well as velocity in side branches.**

■ RESULTS: **Ten patients were studied. At follow-up after initial treatment, 7 of the 10 reconstructions were successful. Compared with the 3 unsuccessful reconstructions, successful reconstructions showed a significantly greater increase in the mean RRT (1185.1% vs. 204.8%; $P = 0.030$) and a greater reduction in mean velocity (44.5% vs. 34.7%; $P = 0.053$) and wall shear stress (49.2% vs. 27.9%; $P = 0.087$). The average velocity in the branches decreased by 10.0% after SOT. There was also a significant difference between the mean reduction in the rate of flow velocity in the aneurysm and the side branches (42.1% vs. 10.0%; $P < 0.001$).**

■ CONCLUSIONS: **We found a significant increase in RRT of successful reconstruction of aneurysms. There may be less effect on the flow in branches arising from VFAs after SOT, whether the aneurysms showed complete occlusion or not.**

INTRODUCTION

With the development of endovascular devices, intracranial stents and flow diverters have become major options for treating vertebral fusiform aneurysms (VFAs).[1-4] However, reconstruction with low metal coverage stents has faced some problems (e.g., high recurrence rate and low occlusion rate). Flow diverters with high metal coverage may overcome these shortcomings, although new concern was raised because the crucial branch might be compromised after deployment of a flow diverter or multiple stents.

Computational fluid dynamics (CFD) is a valuable tool for evaluating aneurysm initiation, growth, rupture, and recurrence,[5-8] and blood flow remodeling via stents or flow diverters has attracted increasing attention in hemodynamic studies. Many studies have shown that the hemodynamic effect of these devices plays an important role in the outcome of intracranial saccular

Key words
- Flow diverter
- Flow reconstruction
- Hemodynamics
- Stent
- Vertebral fusiform aneurysms

Abbreviations and Acronyms
3D: Three-dimensional
CFD: Computational fluid dynamics
DSA: Digital subtraction angiography
PICA: Posteroinferior cerebellar artery
RRT: Relative residual time
SOT: Stent-only treatment
VFA: Vertebral fusiform aneurysm
WSS: Wall shear stress

From the [1]Department of Neurosurgery, The First Affiliated Hospital of Nanchang University, Nanchang University, Nanchang; and [2]Department of Interventional Neuroradiology, Beijing Neurosurgical Institute and Beijing Tiantan Hospital, Capital Medical University, Beijing, China

To whom correspondence should be addressed: Yang Wang, M.D.; Xinjian Yang, M.D., Ph.D. [E-mail: wangyang6877@163.com; yangxinjian@bjttyy.org]

Wenqiang Li and Jian Liu contributed equally to this work.

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aneurysms after endovascular treatment.[9-12] However, the hemodynamic effect of stents or flow diverters on the outcomes of VFAs after reconstruction has been less well studied using CFD. Kallmes et al.[10] and Xiang et al.[13] found that the aneurysms were occluded, although the side branches were still patent, after covering both aneurysms and side branches with a flow diverter. However, the mechanism was unclear. The hemodynamics of the stent-covered branch was not well evaluated based on patient-specific models. Physicians might be interested in the debate about whether the branch would be compromised after deploying a flow diverter or multiple stents.

Using novel virtual stenting technology, we evaluated the hemodynamic alterations of VFAs after reconstruction with stent-only treatment (SOT). The correlation between hemodynamic alterations and angiographic outcomes was analyzed, and the influence of the reconstruction on the side branches was assessed from a hemodynamic viewpoint.

METHODS

The study was approved by our ethics committee. Consent was obtained from the patients or their closest relatives before the study.

Patient Selection

Between September 2014 and December 2015, we reviewed the clinical and radiologic data from our aneurysm database. Because the use of coils might have contributed to hemodynamic alterations after aneurysm embolization, we mainly focused on the hemodynamic effects of stents in the present study. Thus, VFAs with SOT were selected and included in our study. Considering the controversy over VFAs with endovascular treatment, most VFAs were treated conservatively and have had regular follow-up by digital subtraction angiography (DSA)/magnetic resonance angiography. Patients with ruptured aneurysms, recurrent symptoms, or worsened symptoms were treated at our institute.

Patients without angiographic follow-up or three-dimensional (3D) images with sufficient resolution for computational simulation were excluded from our study. After detailed discussions with the patients or their relatives, we included in our study 10 patients who presented with VFAs and underwent SOT.

Dual antiplatelet therapy (100 mg of aspirin and 75 mg of clopidogrel) preoperatively should be administered for at least 3 days for patients with an intracranial stent (such as Enterprise [Cordis Neurovascular, Miami, Florida, USA] and LVIS [MicroVention—Terumo, Tustin, California, USA]), and at least 5 days preoperatively for patients with a Pipeline stent (Coviden/ev3 Neurovascular, Irvine, California, USA). After the procedure, patients with intracranial stent were kept on dual antiplatelet therapy for 6 weeks, and then, aspirin monotherapy was continued for 6 months after the endovascular procedure. For patients with a Pipeline stent, dual antiplatelet therapy was maintained for 3 months postoperatively followed by aspirin monotherapy for 12 months. After stent placement, we use control angiography to evaluate immediate postprocedural hemodynamic changes as immediate angiographic results. The number of overlapping stents was determined according to the location of the aneurysm of the vertebral artery, tortuousness of the parent artery, and findings on control angiogram just after deployment of the first stent. In some cases, a single stent was not sufficient to remodel the blood flow sufficiently and subsequent overlapping stents were deployed.

Angiographic follow-up was performed with DSA or magnetic resonance angiography at 6—14 months. The result was determined by 2 neurointerventionalists (with 5 years of experience in endovascular treatment) who evaluated blinded slides. Disagreements were resolved by a third neurointerventionalist (10 years of experience in endovascular treatment). According to the angiographic outcome, cases were divided into a successful reconstruction group and an unsuccessful reconstruction group. We defined successful reconstruction as a parent artery that showed perfect reconstruction and maintained blood flow through the parent artery and side branches and an aneurysm that showed complete or nearly complete occlusion. Otherwise, the reconstruction was considered unsuccessful. In addition, the side branches were evaluated and compared with preoperative DSA images to identify diameter changes and determine branch patency.

Geometric Reconstruction and Stent Modeling

As reported in our previous studies,[14,15] patient-specific 3D DSA data were obtained, using Geomagic Studio version 12.0 software (Geomagic, Research Triangle Park, North Carolina, USA). The 3D geometry surface was displayed, segmented, and smoothed. The geometries were saved in standard tessellation language format.

Three stent types (Enterprise, LVIS, and Pipeline) were used in the study patients. We also used a novel virtual stenting technique for stent simulation in this study.[15,16] The diameters and number of virtual stent wires used in this technique were simulated based on the stent. The method of overlapping stent simulation was taken from a study by Damiano et al.[17] In addition, we created 2 models for each case (pretreatment and posttreatment) so we could compare the hemodynamic changes before SOT with those afterward.

CFD Simulation and Hemodynamic Analysis

The virtual stent was merged with the aneurysm geometry using ICEM CFD software (ANSYS Inc., Canonsburg, Pennsylvania, USA) to create more than one million finite-volume tetrahedral elements. The maximum element size was set at 0.2 mm, and the element size on stents was set at different sizes for adequate representation of the stent geometry, which was approximately one third the width of the strut of these stents. After meshing, ANSYS CFX 14.0 software (ANSYS Inc.) was used to simulate the hemodynamics. The governing equations underlying the calculation were from the Navier-Stokes formulation, with the assumption of homogeneous, laminar, incompressible blood flow. We treated blood as a Newtonian fluid. The blood vessel wall was assumed to be rigid, with no-slip boundary conditions. The density and dynamic viscosity of blood were specified as $\rho = 1060$ kg/m^3 and $\mu = 0.004$ Pa/second, respectively. A representative pulsatile period velocity profile was obtained using transcranial Doppler imaging and set as the inflow boundary condition. The outlet pressure conditions at outlet arteries in our study were imposed to 0, as reported by Hu et al.[18] For the influence of outlet boundary condition, Hu et al. found that there is no significance difference when considering the outlet boundary conditions affecting the flow reduction of outlet arteries.[18] The flow waveforms were scaled to achieve a mean inlet wall shear stress