High-fidelity virtual stenting: modeling of flow diverter deployment for hemodynamic characterization of complex intracranial aneurysms

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OBJECT Flow diversion via Pipeline Embolization Device (PED) represents the most recent advancement in endovascular therapy of intracranial aneurysms. This exploratory study aims at a proof of concept for an advanced device-modeling tool in conjunction with computational fluid dynamics (CFD) to evaluate flow modification effects by PED in actual, treated cases.

METHODS The authors performed computational modeling of 3 PED-treated complex aneurysm cases. The patient in Case 1 had a fusiform vertebral aneurysm treated with a single PED. In Case 2 the patient had a giant internal carotid artery (ICA) aneurysm treated with 2 PEDs. Case 3 consisted of tandem ICA aneurysms (III-a and III-b) treated by a single PED. The authors' recently developed high-fidelity virtual stenting (HiFIVS) technique was used to recapitulate the clinical deployment process of PEDs in silico for these 3 cases. Pretreatment and posttreatment aneurysmal hemodynamics studies performed using CFD simulation were analyzed. Changes in aneurysmal flow velocity, inflow rate, wall shear stress (WSS), and turnover time were calculated and compared with the clinical outcome.

RESULTS In Case 1 (occluded within the first 3 months), the aneurysm had the most drastic flow reduction after PED placement; the aneurysmal average velocity, inflow rate, and average WSS were decreased by 76.3%, 82.5%, and 74.0%, respectively, whereas the turnover time was increased to 572.1% of its pretreatment value. In Case 2 (occluded at 6 months), aneurysmal average velocity, inflow rate, and average WSS were decreased by 39.4%, 38.6%, and 59.1%, respectively, and turnover time increased to 163.0%. In Case 3, Aneurysm III-a (occluded at 6 months) had a decrease by 38.0%, 28.4%, and 50.9% in average velocity, inflow rate, and average WSS, respectively, and turnover time increased to 139.6%, which was quite similar to Aneurysm II. Surprisingly, the adjacent Aneurysm III-b had more substantial flow reduction (a decrease by 77.7%, 53.0%, and 84.4% in average velocity, inflow rate, and average WSS, respectively, and

ABBREVIATIONS CFD = computational fluid dynamics; FD = flow diverter; HiFIVS = high-fidelity virtual stenting; ICA = internal carotid artery; OphA = ophthalmic artery; PED = Pipeline Embolization Device; PICA = posterior inferior cerebellar artery; VA = vertebral artery; WSS = wall shear stress.

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an increase to 213.0% in turnover time) than Aneurysm III-a, which qualitatively agreed with angiographic observation at 3-month follow-up. However, Aneurysm III-b remained patent at both 6 months and 9 months. A closer examination of the vascular anatomy in Case 3 revealed blood draining to the ophthalmic artery off Aneurysm III-b, which may have prevented its complete thrombosis.

CONCLUSIONS This proof-of-concept study demonstrates that HiFiVS modeling of flow diverter deployment enables detailed characterization of hemodynamic alteration by PED placement. Posttreatment aneurysmal flow reduction may be correlated with aneurysm occlusion outcome. However, predicting aneurysm treatment outcome by flow diverters also requires consideration of other factors, including vascular anatomy.

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KEY WORDS intracranial aneurysm; flow diverter; Pipeline Embolization Device; high-fidelity virtual stenting; computational fluid dynamics; stent modeling; vascular disorders

THE prevalence of intracranial aneurysms is estimated to be 1%–5% in the general population.^{19,20} Aneurysm rupture leads to subarachnoid hemorrhage, and can result in devastating morbidity and mortality as well as high health care costs.²⁰ Flow diversion via flow diverters (FDs) such as the Pipeline Embolization Device (PED, Covidien) is a novel therapeutic method for the treatment of complex intracranial aneurysms, which can be challenging for both conventional microsurgical and endovascular techniques. The PED is a self-expandable, braided, mesh device that diverts blood flow away from the aneurysm sac and thereby induces thrombotic occlusion.⁶ The device can also serve as a scaffold for endothelialization to reconstruct the parent vessel along the diseased segment and restore normal physiological flow conditions.^{6,11,17,23}

Because the PED is novel and its application can be flexible, there is an inherent variability in how these devices are used for different patients and treatment scenarios. Compared with conventional endosaccular therapy, flow diversion rarely leads to immediate aneurysm thrombosis, and the amount of contrast stagnation within the aneurysm sac after PED placement is somewhat subjective. Stacking multiple PEDs could result in more neck coverage and flow reduction, but could also increase the risk of in-stent stenosis and perforator thrombosis. On the other hand, insufficient flow diversion could cause incomplete aneurysm occlusion and even post-PED aneurysm rupture. Therefore, it is essential to understand the effect of FDs on the hemodynamic profile within an aneurysm sac and the subsequent biological responses.

Computational fluid dynamics (CFD) is an efficient method to evaluate the effect of the PED on aneurysmal hemodynamics.^{3,14,24} Quantitative assessment of different deployment scenarios and treatment options can be achieved through modeling to provide insights into the patient-specific hemodynamic changes induced by PED placement. In previous studies,^{12–14,24} we have developed a finite-element method–based high-fidelity virtual stenting (HiFiVS) technique^{12,13} to simulate in silico the mechanical process of implanting PEDs, and we have investigated hemodynamic alterations by different deployment strategies of PEDs.^{14,24} However, the cases used in these earlier virtual experiments were not treated by PEDs in real life. In this proof-of-concept study, we applied our novel computational device modeling workflow to investigate

the flow modifications in real, patient-specific aneurysms treated by PEDs, and examined if there was any correlation between the patients' clinical course and hemodynamic changes induced by FDs.

Methods

Patient Population

Three patients with complex intracranial aneurysms, who were treated in real life with PEDs, were included in this computational study. These cases represented a diverse range of aneurysms with challenging anatomy and would have been difficult to treat with either conventional endovascular or microsurgical techniques. Demographic and clinical information was collected from medical records. The study was approved by the University at Buffalo Institutional Review Board.

Finite-Element Method Modeling of FD Deployment

We created a computer-aided design FD model mimicking a real PED by using an in-house MATLAB code.¹² This virtual PED consisted of 48 strands with 30- μ m diameter with a nominal metal coverage rate of 30%. We used our recently reported finite-element method–based HiFiVS technique^{12,13} to simulate the mechanical process of implanting PEDs into patient-specific aneurysm models. The simulation incorporated all mechanical steps that would affect the final deployed configuration of a PED, including crimping, fitting into a microcatheter, delivering to the lesion, unsheathing, and expanding from the microcatheter. Since PEDs were inherently highly flexible, their final deployed configuration was largely dependent on the deployment process. Thus the mechanical characteristics of the system should be taken into account to ensure the results were as accurate as possible.

Computational Fluid Dynamics Modeling

Computational grids of approximately 1 million and 8 million unstructured polyhedral elements were generated during preprocessing using the finite-volume–based CFD software, Star-CCM+ (CD-adapco) for untreated and treated cases. These grids were used to solve the flow-governing Navier-Stokes equations with the second-order accuracy in Star-CCM+. Velocity and pressure fields were computed under the common assumptions of steady state,

TABLE 1. Demographic and clinical information in 3 patients with complex intracranial aneurysms

Case No.	Age (yrs)	Sex	Aneurysm Characteristics			PED Placement	Outcome
			Location	Type	Size (mm)		
1	66	M	Rt VA	Fusiform, dissecting	13 × 10	4.5 × 25 mm	Complete occlusion at 3 mos
2	65	F	Lt ICA	Saccular, giant	20 × 16	4.5 × 20 mm, 4.5 × 14 mm	Complete occlusion at 6 mos
3	45	F	Rt ICA	Saccular, tandem	III-a: 4 × 3; III-b: 7 × 5	3.75 × 20 mm	III-a: complete occlusion at 6 mos; III-b: not occluded

incompressible, rigid wall, and Newtonian fluid. The inlet mean flow rates extracted from previous reports^{7,25} were used for each anatomical location. The viscosity and the density of blood used in the simulations were 3.5 cP and 1056 kg/m³, respectively.

From CFD simulation results, several flow parameters were calculated to measure the qualitative and quantitative effects of PED treatment on aneurysm hemodynamics, including aneurysmal average velocity, inflow rate, average wall shear stress (WSS), and turnover time. The flow characteristics inside the aneurysm and through the PED struts were visualized using 3D streamlines as well as velocity vectors on a slice plane intersecting the aneurysm sac and the deployed PEDs. The WSS, which represents the friction force between blood and vessel inner surface, was found to play an important role in the aneurysm initiation, growth, and rupture, as well as thrombosis.^{2,4,15,16,25,26} Therefore, we monitored how the interventions changed the WSS distribution as well as zones of high and low WSS. To quantify the pre- and post-PED intraaneurysmal flow activity, magnitudes of aneurysmal velocity and WSS were volume-averaged and surface-averaged inside or on the aneurysm sac, respectively. Flow stasis was quantified by aneurysmal inflow rate and turnover time, defined as the aneurysm sac volume divided by the inflow rate at the neck plane. Increasing aneurysmal flow turnover time can accelerate blood clotting and thrombotic occlusion of the aneurysms.⁹

Results

Patient Information

The clinical and radiographic information is summarized in Table 1. The average aneurysm size was 11 mm. These 3 complex, FD-treated cases include a vertebral artery (VA) dissecting aneurysm, a giant supraclinoid internal carotid artery (ICA) aneurysm, and tandem aneurysms at the ICA ophthalmic segment. All patients were treated with aspirin and clopidogrel prior to PED placement. The detailed patient information follows.

Case 1: Fusiform VA Aneurysm

A 66-year-old man was found to have a fusiform right VA aneurysm (Aneurysm I) during workup of headache (Fig. 1). The morphology of the aneurysm suggested that it could be dissecting in nature, and the segmental defect appeared to involve the entire circumference of the VA as well as the posterior inferior cerebellar artery (PICA). Standard endovascular coiling or clipping would be challenging options, and VA ligation (either endovascularly or

microsurgically) proximal to the PICA was also not possible because the right VA was dominant for this patient. This patient eventually underwent single PED (4.5 × 25 mm) placement for the treatment of the aneurysm. Post-operative angiograms obtained at 3 months demonstrated complete occlusion of the aneurysm with patent right PICA (Fig. 1). The patient has had no new complications and is clinically intact. This patient was treated with both aspirin and clopidogrel after FD treatment. Clopidogrel was then stopped 3 months after PED placement when the aneurysm was completely occluded. However, the aspirin regimen was continued for this patient.

Case 2: Wide-Based Supraclinoid ICA Aneurysm

A 65-year-old woman presented with decreased vision of her left eye and was found to have a large, wide-based, left ophthalmic-segment ICA aneurysm (Aneurysm II) that measured 20 × 16 mm (Fig. 2). Although the aneurysm could be treated with standard stent-assisted coiling, the large size and wide neck made it prone for recanalization. Moreover, since the saccular defect of the arterial wall was along the outside curve of the parent vessel, the aneurysm sac was susceptible to strong impingement flow. Because of these abnormalities and flow conditions, flow diversion appeared to be a good strategy to reduce the flow into the aneurysm and disperse the inflow jet. Considering the strong inflow impingement, this patient was treated with 2 PEDs (4.5 × 20 mm, 4.5 × 14 mm). This ICA aneurysm was occluded on 6-month follow-up imaging (Fig. 2). Because of the size of the aneurysm, clopidogrel was continued for 6 months in this patient after PED placement, and was stopped after postoperative angiograms showed complete occlusion. However, this patient had been on aspirin since the PED was placed.

FIG. 1. Case 1. Angiograms obtained at the initial pretreatment examination showing a fusiform VA aneurysm in a 66-year-old man, and post-treatment 3-month follow-up imaging showing the occluded lesion.

FIG. 2. Case 2. Angiograms obtained at the initial pretreatment examination showing a wide-based supraclinoid ICA aneurysm in a 65-year-old woman, and posttreatment 6-month follow-up imaging showing the occluded lesion.

Case 3: Tandem ICA Aneurysms

A 45-year-old woman with significant family history of intracranial aneurysms was found to have multiple ICA aneurysms. There were tandem saccular aneurysms along the ophthalmic segment of the right ICA: a larger, multilobular aneurysm (Aneurysm III-a) lay along the inner curve of the parent vessel, and a smaller aneurysm (Aneurysm III-b) lay along the outside curve (Fig. 3). The complex configuration of the 2 aneurysms made them less ideal for primary coiling or stent-assisted coiling, and it was suspected that the entire vessel segment was abnormal. This patient was treated with 1 PED (3.75 × 20 mm). On the 3-month follow-up images (Fig. 3), although there was increased contrast stasis in both aneurysms, neither was completely occluded. On 6- and 9-month follow-up images (Fig. 3) Aneurysm III-a was completely occluded, whereas Aneurysm III-b continued to have small, faint residual filling. In all of the follow-up images, the ophthalmic artery (OphA) was patent. This patient had a history of factor V Leiden and remained on aspirin and clopidogrel according to recommendation from a hematology specialist.

Results of PED Deployment and Hemodynamic Analysis

Case 1 Results

In this case, 1 PED (4.5 × 25 mm) was virtually deployed using the HiFiVS modeling method to recapitulate the clinical scenario as shown in Fig. 4A. In the untreated

case, there was a strong inflow jet impinging on the distal end of this fusiform aneurysm. When the PED was deployed, a majority of the flow was diverted away from the aneurysm sac and was kept in the parent vessel conduit, as demonstrated by the 3D streamlines in Fig. 4B and the slice-plane velocity vectors in Fig. 4C. The WSS distributions for the untreated and treated scenarios are given in Fig. 4D. It can be observed that the area with higher WSS coincided with the location of the impingement jet region in the lesion pretreatment. The PED deployment eliminated the higher WSS regions in the lesion posttreatment.

Compared with pretreatment case, the aneurysmal average velocity, inflow rate, and average WSS were decreased by 76.3%, 82.5%, and 74.0%, respectively, whereas the turnover time was increased to 572.1% (Fig. 5). At the 3-month follow-up, there was no evidence of flow into the aneurysm, which could be predicted by findings from the CFD simulations because all quantified hemodynamic factors were highly suggestive of rapid aneurysm occlusion. Furthermore, CFD flow visualization showed that the flow streamlines diverted away from the aneurysm traveled in the conduit enclosed by the PED surface. The PED in this case not only cured the aneurysm, but also reconstructed the parent vessel.

Case 2 Results

The second case consisted of a giant ICA aneurysm. This patient was treated with 2 overlapping PEDs (4.5 × 20 mm and 4.5 × 14 mm, Fig. 6A), and we calculated flow parameters after each FD deployment, denoted by II(T1) and II(T2). Case II(T1) is a hypothetical case that we simulated with only 1 PED to see how much additional flow diversion was introduced by adding a second PED.

Although this was a sidewall, saccular aneurysm, the 3D streamlines (Fig. 6B) and middle-plane velocity vectors (Fig. 6C) revealed that there was a strong impingement flow jet on the distal side of the lesion. After placement of single PED, the velocity magnitude of the flow jet did decrease, although its flow structure remained quite patent. Placement of the second PED significantly reduced velocity, albeit the impingement jet remained. The WSS distributions revealed that zones of higher WSS were greatly decreased after placement of the PEDs (Fig. 6D).

Quantitative analysis demonstrated that, with the hy-

FIG. 3. Case 3. Angiograms obtained at the initial pretreatment examination showing tandem ICA aneurysms in a 45-year-old woman, and posttreatment 3-, 6-, and 9-month follow-up imaging showing the still-patent Aneurysm III-b at 6 and 9 months.

pothetical 1 PED treatment, aneurysmal average velocity, inflow rate, and average WSS decreased by 20.3%, 20.0%, and 31.8%, respectively, and turnover time increased to 125.0% (Fig. 5). After deploying the second PED (the real treatment), average velocity, inflow rate, and average WSS decreased almost double—by 39.4%, 38.6%, and 59.1%, respectively. Moreover, turnover time increased by approximately 40% after deploying the second PED (from 125.0% to 163.0%). Although the effect of flow reduction by the 2 PEDs in this aneurysm was not as substantial as in Aneurysm I, we believe that the second PED was necessary and was apparently enough, because Aneurysm II was completely occluded on the 6-month follow-up imaging sequences (Fig. 2).

Case 3 Results

Case 3 proved to be an interesting one, not only because it contained tandem aneurysms treated by a single PED, but also because of the surprising CFD simulation results. The right ICA lesions shown in Fig. 7A as Aneurysms III-a and III-b were treated with a single PED (3.75 × 20 mm). It should be mentioned that the OphA branches off from Aneurysm III-b.

The 3D streamlines in Fig. 7B and the middle-plane velocity vector plots in Fig. 7C demonstrated that the inflow velocity in both aneurysms decreased after the PED placement. The WSS contours revealed that in both aneurysms the zones of higher WSS were decreased after PED placement (Fig. 7D). However, Aneurysm III-a appeared to still contain high WSS after PED deployment compared with Aneurysm III-b.

Quantitative calculations from CFD showed that Aneurysm III-a had decreased by 38.0%, 28.4%, and 50.9% in aneurysmal average velocity, inflow rate, and average WSS, respectively, and an increase to 139.6% in turnover time (Fig. 5), which was quite similar to Aneurysm II. Surprisingly, the adjacent Aneurysm III-b had more substantial flow reduction (a decrease by 77.7%, 53.0%, and 84.4% in average velocity, inflow rate, and average WSS, respectively, and an increase to 213.0% in turnover time) than Aneurysm III-a.

On the 3-month follow-up angiograms (Fig. 3), there was stasis of contrast within both aneurysms, but more flow into Aneurysm III-a, which was consistent with our findings from CFD simulation (less flow reduction). At 6- and 9-month follow-ups, angiography showed that Aneurysm III-a was completely opaque, but Aneurysm III-b had persistent faint filling. This seemed unexpected because Aneurysm III-b had more reduction in aneurysmal velocity, inflow rate, and WSS, and more increase in turnover time. A closer look at the vascular anatomy of this case showed draining of blood to the OphA through Aneurysm III-b, which may have prevented its occlusion.

Correlation Between Hemodynamic Modification and Treatment Outcome

The results of hemodynamic alteration by PED deployment shown in Fig. 5 reveal a possible correlation between flow reduction (in aneurysmal velocity, inflow rate, and WSS), as well as increase in turnover time and aneurysm occlusion rate, with the exception of Aneurysm

FIG. 4. Pretreatment and posttreatment hemodynamics in Case 1. **A:** Aneurysm model without and with PED deployment. **B:** 3D streamlines. **C:** Intraaneurysmal velocity vectors on a representative plane. **D:** WSS distributions. I(U) = untreated; I(T) = treated by 1 PED. Figure is available in color online only.

III-b. Aneurysm I had the largest flow reduction and turnover time increase, and it was most rapidly occluded—within 3 months. Aneurysm II (treated with 2 PEDs) and Aneurysm III-a had similar flow attenuation, and both were occluded on 6-month follow-up imaging. However, Aneurysm III-b was not completely occluded due to the draining side branch, although its aneurysmal flow was drastically reduced. This demonstrates that although hemodynamic alteration is the main mechanism of flow diversion treatment, it is not the only factor for aneurysmal occlusion. Other factors such as vascular anatomy are also important.

Discussion

Endoluminal therapy with flow diversion is a novel strategy for treating intracranial aneurysms and has gained notable enthusiasm after promising results from

FIG. 5. Bar graphs showing quantitative comparison of PED-induced flow reduction in relation to the occlusion outcome in the 4 aneurysms. **A:** Average aneurysmal velocity reduction. **B:** Aneurysmal inflow rate reduction. **C:** Average aneurysmal WSS reduction. **D:** Relative aneurysmal turnover time. The labels I, II(T2), III-a, and III-b denote modeling results of the actual treatment in Aneurysms I, II, III-a, and III-b, respectively. Note that Aneurysm III-b had blood drainage to the OphA. The label II(T1) denotes hypothetical results of Aneurysm II being treated by the first PED only to see how much additional flow diversion was induced by adding the second PED.

large multicenter clinical trials.^{1,17} A recent case-controlled study also demonstrated that the PED could provide higher occlusion rates for large aneurysms than could coiling.⁵ Nevertheless, although FDs can provide better neck reconstruction and reduce the risk of recanalization, they do not provide immediate dome protection and cannot be used at arterial bifurcations.¹⁰ One could argue that it is the PED's effect on changing intraaneurysmal hemodynamic profile that contributes to aneurysm thrombosis; yet such changes have been poorly understood.

To address the need to evaluate a relationship between the changing intraaneurysmal hemodynamic profile and aneurysm thrombosis, we conducted the current exploratory, proof-of-concept study in which our novel computational device modeling HiFiVS workflow^{12,13} was combined with CFD to investigate the flow modifications of real, patient-specific aneurysms treated by PEDs. Since the PED deployment is a highly variable process, an advanced modeling method is needed to realistically capture this process and its result. The HiFiVS technique has the unique capability to recapitulate the entire mechanical and maneuvering processes of FD deployment and has been rigorously validated by in vitro experiments.¹³ Therefore, it can serve as a virtual stenting tool to reproduce clinically realistic insertion strategies in silico and enable accurate hemodynamic simulation via CFD, either a priori (to plan treatment) or a posteriori (to understand cases). We believe

it is critical to inform the field in a timely fashion of the availability of such advanced computational methods and their potential for helping clinical management of aneurysms.

Other investigators have also studied hemodynamic changes within aneurysms after flow diversion by using in vitro experiments or CFD with simplified FD geometry representation. Using particle-image velocimetry measurement in an aneurysm phantom, Roszelle et al.²¹ have shown that fluid dynamic activity reduction by a single PED was similar to that induced by 3 overlapping Enterprise stents. Kulcsár et al.⁸ used a simplified stent patch to model the effect of SILK FDs in 8 paraophthalmic aneurysms. They found that reduction in intraaneurysmal flow velocities and WSS (the relative change in the intraaneurysmal flow profile after flow diversion, not the absolute value of velocity and WSS) was qualitatively predictive of aneurysm thrombosis.

Our patient-specific modeling results based on the limited number of complex aneurysm cases have demonstrated that, in general, the aneurysmal occlusion rate is associated with the amount of hemodynamic modifications after treatment. However, caution is called for. The "surprise" of the treatment outcome in Aneurysm III-b indicates that aneurysmal occlusion after FD treatment may be more complex than flow reduction alone. The presence of the draining OphA off Aneurysm III-b probably delayed

FIG. 6. Pretreatment and posttreatment hemodynamics in Case 2. **A:** Aneurysm model without and with PED deployment. **B:** 3D streamlines. **C:** Intraaneurysmal velocity vectors on a representative plane. **D:** WSS distributions. II(U) = untreated; II(T1) = treated by 1 PED (hypothetical); II(T2) = treated by 2 PEDs. Figure is available in color online only.

the thrombosis of this aneurysm. Even through the blood in the aneurysm did slow down (through the FD), it was constantly refreshed due to the drainage, and was thereby unable to thrombose. This may represent an “entry remnant” situation in the proposed grading scale for the angiographic assessment of aneurysms treated by FDs.¹⁸ Other factors could also impact treatment outcome, including the nature of the vessel wall, the type of thrombus, antiplatelet effects, aneurysm location, aneurysm size, branching anatomy, branches arising from the aneurysm, type of aneurysm, rupture status, age of patient, comorbidities, and so on. The reason complete occlusion was achieved for the fusiform Aneurysm I with patent PICA, whereas persistent residual filling was observed for Aneurysm III-b with patent OphA was not clearly understood. This requires further investigations. Future studies should focus on analyzing a large number of aneurysms treated by FDs and

building statistical models to correlate changes in hemodynamic parameters with occlusion status and time. Such information could potentially help to optimize aneurysm treatment planning by FDs.

This study has a number of limitations. First, as a pilot study for applying the most sophisticated FD modeling techniques to real treatment cases, it does not have the statistical power to draw solid conclusions on FD treatment. Second, patient-specific inlet flow boundary conditions (which would require phase-contrast MR or transcranial Doppler measurement) were unavailable, and instead typical flow rates from the literature were applied as the inlet boundary condition for CFD simulation. However, this assumption should have minimal effect on the analyses because we only compared the hemodynamic changes instead of absolute values. Third, like most CFD studies in large-vessel and aneurysm blood flow simulations, ad-

FIG. 7. Pretreatment and posttreatment hemodynamics in Case 3. **A:** Tandem aneurysm model without and with PED deployment. **B:** 3D streamlines. **C:** Intraaneurysmal velocity vectors on a representative plane. **D:** WSS distributions. III(U) = untreated Aneurysms III-a and III-b; III(T) = Aneurysms III-a and III-b treated by a single PED. Figure is available in color online only.

ditional simplifying assumptions such as rigid wall and Newtonian fluid were also applied, with accepted justifications.²²

Despite these limitations, the results of this proof-of-concept study demonstrated the feasibility of quantitatively accessing the level of flow reduction after PED placement for patient-specific aneurysms by using our novel computational device modeling HiFiVS workflow and correlating the change in flow parameters with aneurysm occlusion and time. The study reaffirmed, through quantitative hemodynamic analysis, the currently accepted concept that higher flow reduction leads to a better chance of aneurysm occlusion.

Conclusions

This proof-of-concept study demonstrates that high-fi-

delity computational modeling of FD deployment enables detailed characterization of hemodynamic alteration by PED placement. Posttreatment aneurysmal flow reduction may be correlated with aneurysm occlusion outcome. However, predicting aneurysm treatment outcome by FDs also requires consideration of other factors including vascular anatomy.

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