INTRODUCTION
Neurovascular flow diverters (FD) have recently emerged as a novel paradigm of treating some surgically challenging intracranial aneurysms (IA) such as those with wide neck or thin vascular wall\(^1\). The mesh of a braided FD is dense enough (~30% metal coverage) to divert majority of blood flow (~85%) for a thrombotic process inside IA dome without soliciting traditional coils. Meanwhile, small IA inflow is still maintained to keep nearby perforators and side branches patent. Endothelial pavement is expected to form inside the FD later to reconstruct a new flow conduit that eventually obliterates the IA.

Current study utilized a numerical modeling workflow tailored for the unique behavior of woven FDs aiming to capture their clinic operations and final positioning. The resulted vessel straightening, FD conformity to vessel geometry were then analyzed to give further insights for clinical observations\(^1\). This study also contributed hemodynamics analysis of flow diverters in the future.

METHODS
Abaqus/Explicit (SIMULIA, Providence, RI) was used for quasi-static finite element analysis (FEA) of FD. One fusiform and one sidewall aneurysm geometry were chosen. Anisotropic pseudo-elastic strain energy density function (Fung model: Eq 1) was applied to a thin-walled tube model to estimate the elastic stiffness of pre-stressed vessel wall\(^2\). Parameters in Fung model were evaluated by averaged values from surveyed IA (\(c=0.3, A_1=17.58, A_2=12.19, A_3=3.785, A_4=4.96\))\(^3\). The obtained elastic modulus was 9MPa under 100mmHg blood pressure. Poisson ratio \(\nu\) was chosen to be 0.45.

\[
W = \frac{c}{2} \left(e^Q - 1\right), \quad Q = A_1 E_1^2 + A_4 E_2^2 + 2A_1 E_1 E_3 + A_4 E_2^2 \quad \text{Eq.1}
\]

Pipeline™ Embolization Device (PED, Covidien, MA, USA) was used for FD modeling. An in-house algorithm was developed to generate the 3D beam element mesh for PED model (F1 model: outer radius \(R=2.25\)mm, length \(L=13\)mm, braiding angle \(\varphi=75^\circ\); S1 model: \(R=1.75, L=13.5\)mm, \(\varphi=71.5^\circ\)). Component strand diameter \(d=30\)μm applies to both PED models.

PED model was first crimped and then fitted into a microcatheter. The microcatheter and PED were delivered to the target site later. The delivery of PED was accomplished with the guidance of a vasculature determined pathway. To recap the releasing process, a protective coil model and a pusher model were also included (Fig.1). The functionalities of these two parts in a controlled expansion were realized through their interactions with the woven construct.

The final deformed PED in wire feature was then swept with strand thickness into 3D solid representation for future use. Figure 2 demonstrates the modeling workflow. General contact algorithm was chosen to model the interaction among PED strands. Contact pairs were used for other interactions. Friction coefficients between surfaces were summarized in Table 1. Kinematic coupling was used to represent the protective coil in constraining the distal end. Co-Cr-Ni alloy property of PED was modeled as: \(E=206\)GPa, \(\sigma_y=2.8\)GPa at 0.2% plastic strain, \(v=0.3\), density \(\rho=8\)g/cm\(^3\). Microcatheter was modeled using shell element (\(E=1.2\)GPa, \(v=0.45\), \(\rho=1\)g/cm\(^3\), thickness=0.08mm).
Results and discussion

Dehiscence ratio $\lambda$ was defined (Fig.3) for assess of PED conformity to vessel wall (fusiform $\lambda_1=0.11$, sidewall $\lambda_2=0.176$). The change of artery angle was barely noticeable with angle difference $\alpha_1<0.01^\circ$ (fusiform) and $\alpha_2<0.5^\circ$ (sidewall). Figure 4 demonstrates the comparison of silhouettes of each vessel on cutting plane before and after implantation. Figure 5 shows stepwise procedures of modeling.

Conclusion

Simulation results revealed that the PED model applied very small straightening to parent vessel. But its relatively high dehiscence ratio indicates woven structure stent is intrinsically less compliable to vessel wall. Super-elasticity of PED endows considerable foreshortening to the device, thus caution must be prescribed to its clinical deployment. In vitro validation of the results would further prove this method as valuable tool in FD treatment planning.

Reference