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Computer modeling of deployment and mechanical expansion of neurovascular flow diverter in patient-specific intracranial aneurysms

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ABSTRACT

Flow diverter (FD) is an emerging neurovascular device based on self-expandable braided stent for treating intracranial aneurysms. Variability in FD outcome has underscored a need for investigating the hemodynamic effect of fully deployed FD in patient-specific aneurysms. Image-based computational fluid dynamics, which can provide important hemodynamic insight, requires accurate representation of FD in deployed states. We developed a finite element analysis (FEA) based workflow for simulating mechanical deployment of FD in patient-specific aneurysms. We constructed FD models of interlaced wires emulating the Pipeline Embolization Device, using 3D finite beam elements to account for interactions between stent strands, and between the stent and other components. The FEA analysis encompasses all steps that affect the final deployed configuration including stent crimping, delivery and expansion. Besides the stent, modeling also includes key components of the FD delivery system such as microcatheter, pusher, and distal coil. Coordinated maneuver of these components allowed the workflow to mimic clinical operation of FD deployment and to explore clinical strategies. The workflow was applied to two patient-specific aneurysms. Parametric study indicated consistency of the deployment result against different friction conditions, but excessive intra-stent friction should be avoided. This study demonstrates for the first time mechanical modeling of braided FD stent deployment in cerebral vasculature to produce realistic deployed configuration, thus paving the way for accurate CFD analysis of flow diverters for reliable prediction and optimization of treatment outcome.

1. Introduction

Neurovascular flow diverter (FD) is an emerging paradigm for treating traditionally difficult intracranial aneurysm such as wide-necked or fusiform aneurysms (Nelson et al., 2011). It is a self-expandable, tube-shaped metallic stent with fine braided mesh delivered via a catheter. Owing to its low porosity and high pore density, FD is effective at reducing blood inflow to the aneurysm sac, promoting intra-aneurysm thrombosis while keeping the adjacent arterial perforators unblocked. Endothelialization on the stent inner surface forms a new blood flow conduit within months that bypasses the obliterated aneurysm (Szikora et al., 2010).

While this novel intervention has achieved clinical success in an increasing number of challenging aneurysm cases, serious complications such as delayed post-treatment hemorrhage have also been reported (Byrne et al., 2010; Siddiqui et al., 2012). Several contributing factors have been hypothesized including extended aneurysm occlusion time leading to thrombosis-related aneurysm wall weakening (Kulcsar et al., 2011) and post-treatment pressure increase inside the aneurysm dome (Cebral et al., 2011). These hypotheses essentially attribute the variability of clinical outcomes to the patient-specific modification of hemodynamics, which significantly influences endothelialization, thrombosis and wall remodeling. Therefore, knowledge of detailed hemodynamics modified by FD placement is critical to the prediction of treatment outcome.

Image-based computational fluid dynamics (CFD) analysis can potentially provide important insight for this purpose but requires realistic representations of FD in deployed states. This presents challenges to the numerical simulation of stent implantation, since previous methods do not capture clinically realistic FD deployment processes and cannot reproduce the highly variable deployed configurations.

In light of the increasing clinical need for accurate CFD analysis of FD treatment and the inability of current numerical methods to produce realistically expanded FD geometries, we have developed a virtual FD deployment method using finite element analysis

Abbreviations: CFD, computational fluid dynamics; FD, flow diverter; FEA, finite element analysis.

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(FEA). In this approach we model the main steps involved in FD stent deployment in patient-specific aneurysm geometry to obtain realistic final FD configuration. Aside from being a prerequisite in accurate CFD analysis, this method can investigate FD deployment strategies employed by operating clinicians, as well as evaluate the mechanical characteristics of FD stents.

2. Methods

Our FD deployment modeling workflow (Fig. 1) uses these strategies:

(1). FD stent is modeled by 3D finite beam element because of the slender shape of its helical component strands.
(2). The entire deployment process is modeled from stent crimping (packaging), fitting into a microcatheter, maneuver and delivery of the stent-microcatheter system, to stent release from the microcatherter.
(3). Several key components of the FD delivery system are also modeled (Fig. 2). They are found essential to the final deployed configuration clinically. The crimper is modeled to crimp the stent radially; the microcatheter is simplified as a thin-walled cylindrical tube to deploy the stent; the distal coil constraining the stent distal end is modeled by a master-point kinetically coupled with the stent's distal end; the pusher at the proximal end of the stent is simplified as a cylinder with rigid element mesh.
(4). During stent release, operations on the distal coil, microcatheter, and pusher are coordinated to reproduce desired deployment results (Section 2.6).
(5). The deployed FD stent geometry is swept into a 3D solid model for conformity assessment and future CFD analysis.

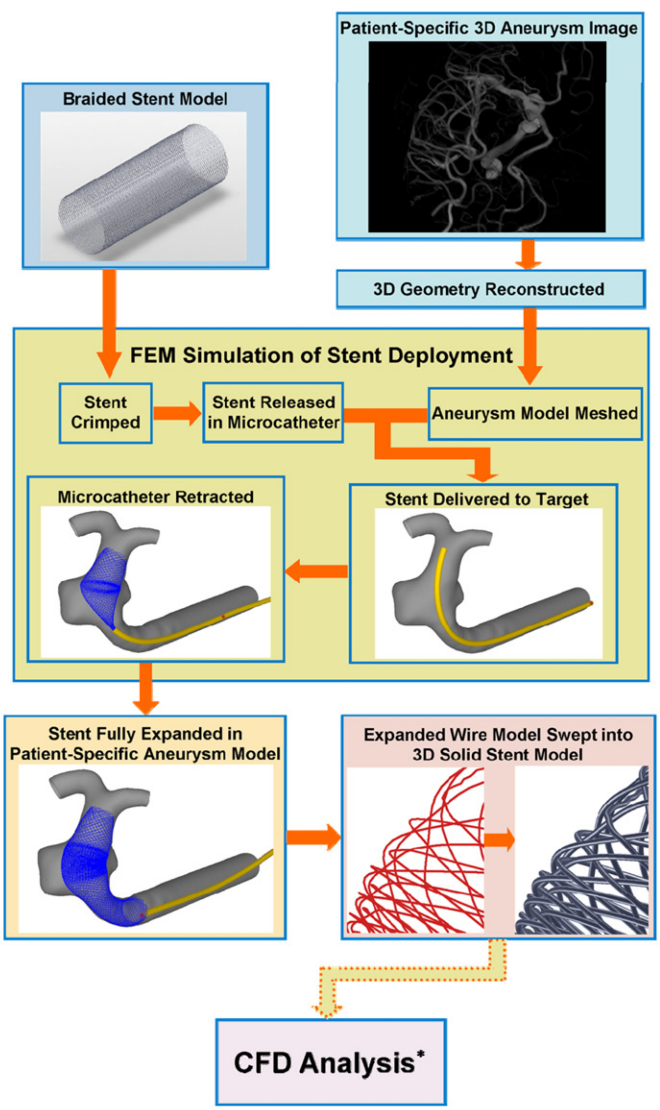

Fig. 1. Modeling workflow for flow diverter (braided stent) deployment in patient-specific aneurysms. *The final step of CFD analysis is not included in the current report. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

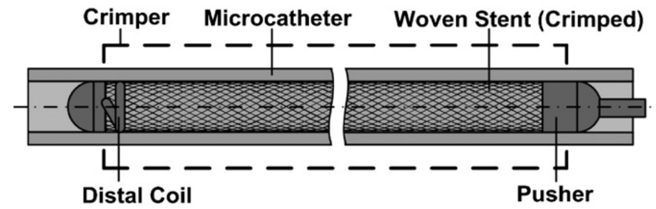

Fig. 2. Schema of key components of the simulated FD deployment system mimicking the Pipeline Embolization Device (Covidien, Irvine, CA).

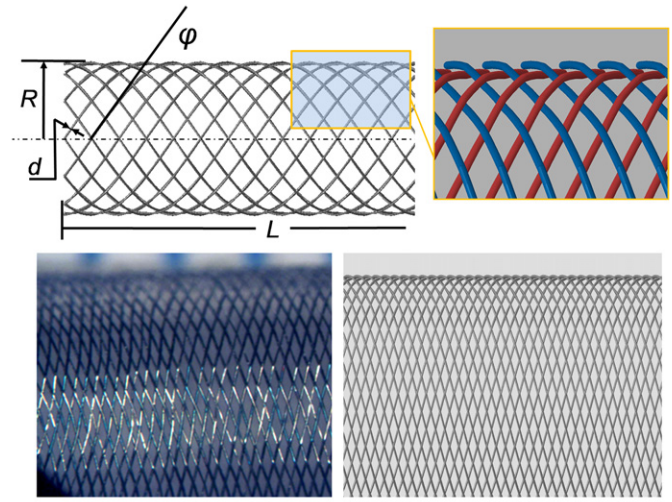

Fig. 3. Braided-stent model emulating the Pipeline Embolization Device. Top: design variables (*R*, outer radius; *d*, strand thickness; *L*, stent axial length; *φ*, braiding angle) and braiding details (Red, left-handed helical strands; Blue, right-handed helical strands). Bottom left: photograph of a Pipeline FD sample. Bottom right: generated 3D solid model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1. *Braided stent geometry generation*

We generated the braided stent wire pattern based on the Pipeline Embolization Device (Covidien, Irvine, CA), currently the only commercial FD approved by FDA. It is a self-expandable, cylindrically-shaped stent with braided structure principally composed of Cobalt–Chromium–Nickel (Co–Cr–Ni) alloy strands.

In building the stent geometry (Fig. 3, top), component helical strands were wound in clockwise and counter-clockwise directions following a mathematical description (Kim et al., 2008a) (Supplement Part 1). Two FD models (F1 and S1) as specified in Table 1 were created emulating the Pipeline Embolization Device of different sizes, with F1 replicating an actual FD sample shown in Fig. 3 (bottom). Their dimensions were checked using CAD programs to ensure geometric accuracy.