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The hemodynamic alterations induced by the vascular angular deformation in stent-assisted coiling of bifurcation aneurysms

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ABSTRACT

The hemodynamic changes induced by stent deployment and vascular remodeling in bifurcation aneurysms were investigated using computational fluid dynamics. The stent deployment reduced the intra-aneurysmal flow activity by decreasing the mean velocity, mean kinetic energy, mean wall shear stress, and mean vorticity. These hemodynamic parameters increased with an increase in the branching angle because of the vessel deformation caused by stent straightening. The maximum wall shear stress and its spatial gradient occurred near the neck of the aneurysm in the stented left daughter vessel, whereas a maximum oscillatory shear index was detected near the neck of the right aneurysm of the right daughter vessel. Theses parameters, which might be related to the recurrence of aneurysms, were also increased by stent-induced vessel deformation.

1. Introduction

An intracranial aneurysm is a cerebrovascular disorder in which the arterial wall weakens—resulting in localized dilation. Rupture of aneurysms causes sub-arachnoid hemorrhages, which are associated with high mortality and morbidity [1–3]. Interventional thromboembolization by endovascular insertion of coils is currently the most popular treatment to prevent the rupture of aneurysms. Thin platinum coils are inserted into the aneurysmal sac, where they form a thrombus that obliterates the aneurysm. Coil embolization of a wide neck aneurysm can be challenging and may not be effective [4] because of coil herniation. In recent years, stent-assisted coil embolization—in which the flexible stent acts as a supporting bridge to prevent herniation of aneurysm coils—has been widely used. The stent can divert flow into the aneurysmal sac and prevent coil herniation; therefore, stent-assisted coil embolization promotes the occlusion of incompletely coiled aneurysms and lowers the risk of recanalization compared with non-stenting embolization [5–9]. Various stent configurations have been used for bifurcation aneurysms [10], and deployment of a flexible stent may deform the host artery because of the mechanical interaction between stent and vessel. The bifurcation angle remodeling associated with stent placement has been investigated in the carotid arteries [11], anterior communicating arteries [12], and intracranial arteries [13]. The immediate and delayed angular remodeling after stent deployment can affect thromboembolization efficacy and aneurysm recurrence because alterations of the vessel bifurcation geometry can alter the hemodynamics in aneurysms.

Computational and experimental studies have been conducted using idealized or patient-specific models to investigate the intra-aneurysmal hemodynamic changes caused by stents [10,14–21]. Meng et al. [17] and Wang et al. [21] investigated the hemodynamic alterations in idealized saccular aneurysm models—side wall and terminal aneurysm models—before and after stent placement using computational fluid dynamic (CFD) methods. Canton et al. [15] measured changes in flow dynamics using particle image velocimetry in bifurcating cerebral aneurysm models after a Neuroform® stent placement and concluded that the magnitude of the velocity of the jet entering the sac was reduced by up to 11%. Tateshima et al. [20] studied the hemodynamic effect of Neuroform® stent placement across the necks of patient-specific aneurysm models and concluded that the stents significantly altered flow velocity and flow structure in aneurysms. Tang et al. [19] studied the hemodynamic effects of aneurysm neck size after stenting and concluded that the volume flow rate of blood entering the aneurysm over the entire cardiac cycle could be reduced by $>50\%$ after the endovascular operation. Most of these studies focused on the intra-aneurysmal hemodynamic changes caused by the inserted stent; however, the hemodynamic

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alterations caused by vessel deformation after stenting—which may affect the efficacy of thromboembolization and recurrence of aneurysms—have not been studied to date.

Recently, using patient-specific CFD analysis, Gao et al. [22,23] observed significant hemodynamic alterations near the neck of an intracranial bifurcation aneurysm caused by stent-induced angular remodeling. The authors virtually removed the aneurysm by using an aneurysm-capping method and showed that stent-induced angular remodeling resulted in the migration and narrowing of the flow impingement zone and a decrease in apical pressure. Given that the CFD study focused on the hemodynamic changes in completely thromboembolized aneurysms after long-term remodeling of stented aneurysms, it did not consider the deployed stent and coils inside an aneurysmal sac, which can have a significant influence on intra-aneurysmal hemodynamics. The immediate vascular remodeling caused by straightening of a stent after stent-assisted coiling treatment may affect the efficacy of thrombus formation inside the aneurysmal sac. However, the intra-aneurysmal hemodynamic changes caused by vascular deformation have not been investigated. In the present study, we have modeled a deployed stent and coils inside an aneurysmal sac of the basilar bifurcation arteries, and investigated the hemodynamic changes induced by the angular deformation caused by straightening of the stent; the hemodynamic parameters in the wide neck aneurysms were computed, and the effect of bifurcation angle remodeling on the effectiveness of aneurysm embolization was discussed.

2. Methods

2.1. Aneurysm and stent modeling

Two wide neck aneurysms located at the tip of a basilar arterial bifurcation were constructed using solid modeling software (SolidWorks, Dassault Systems, Concord, NH) to simulate a terminal aneurysm occurring at the tip of a basilar arterial bifurcation. The present study used 2 idealized aneurysm models. The wide neck basilar aneurysms from the patient angiograms were idealized as half-sphere aneurysms occurring at the tip of the symmetric Y-bifurcations. The aneurysm diameter, basilar artery diameter and neck width for the small and medium wide neck aneurysm model were obtained from the references [10,24]. The maximum diameters of the small and medium wide neck aneurysms were 4 mm and 8 mm, respectively, and the aspect ratios (ratio of dome height to neck width) of these models were kept constant at 0.75 (Fig. 1). The neck width (NW), dome diameter (DD), dome height (DH), and artery diameter (AD) of the small wide neck aneurysm with a maximum diameter of 4 mm measured 4 mm, 4 mm, 3 mm, and 2.7 mm, respectively. The NW, DD, DH, and AD of the medium wide neck aneurysm with a maximum diameter of 8 mm measured 8 mm, 8 mm, 6 mm, and 2.7 mm, respectively. A self-expanding stent was assumed to be inserted into the left daughter branch of the bifurcation. The stent deployed in the left branch of the bifurcation was modeled as a mesh-like structure, where each closed cell assumed the shape of a rhombus. We modeled the closed cell stent because the stent with an open cell structure might generate the prolapse of the struts with cell opening, when it is located in a curved segment. Moreover, the sharp edges of the cell opening would generate singularities and instabilities in the computational analysis as well as require fine grids for stent modeling. Although the stent porosity might affect the hemodynamics of the aneurysms [25], the stent design (strut pattern) prevents the intra-aneurysmal flow from being noticeably affected [10,26]. The strut size was based on an intracranial self-expanding stent [27], and each cell was closed in order to facilitate strut modeling and computational stability. The stent had a length of 10 mm and an outer diameter of 2.7 mm, while the strut had a width of 0.06 mm and thickness of 0.065 mm (Fig. 1).

The stent deployment inside the computational vessel model was performed using the simplified fast virtual stenting (FVS) method. Instead of analyzing the large deformation of the nitinol stent and the hyperelastic vessel using finite element methods, the simplex mesh was arranged as a virtual cylinder of 2.7 mm in diameter and aligned along the centerline of the bifurcating vessels. The stent was inserted in the cylinder and flexed, and the virtual cylinder was removed after positioning the stent in the vessel. The stent was radially expanded by manually repositioning the node points of stents outward to the vessel to account for nodes contact and smoothness. Although the mechanical properties of the stent and vessel deformability were neglected in FVS, the final configuration of the stent inside the vessel showed acceptable differences compared to the structural analysis based on FEM [28] and in vitro experiments [29].

Following insertion of the flexible coil wires into the aneurysmal sac, the randomly entangled wires formed a sponge-like volume inside the aneurysm. The intra-aneurysmal coil modeling was difficult because of the random geometry of the coils and the

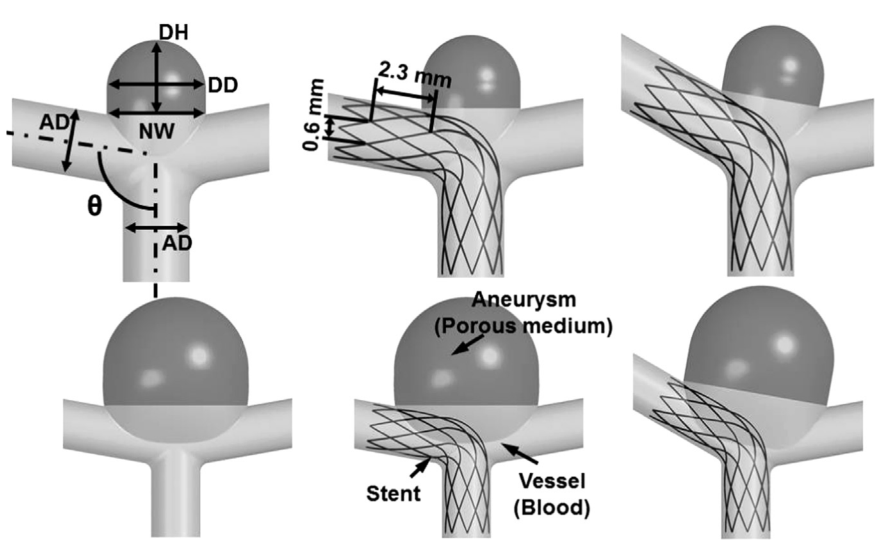

Fig. 1. Bifurcation aneurysm and stent geometry. Abbreviations: AD, artery diameter; DD, dome diameter; DH, dome height; NW, neck width; and θ, branching angle. The coiled aneurysm sac is modeled as a porous domain and blood in the arteries is modeled as a fluid domain.