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Investigation of the hemodynamics of a juxtarenal aortic aneurysm with intervention by dual-stents strategy

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ABSTRACT

Objective: To study the feasibility of using two stents (a combination of multilayer stent [MS] and stent graft [SG]) in the treatment of a juxtarenal aortic aneurysm that involves a significant branch artery and to determine the advantages and disadvantages of using SGs upstream and downstream from the aneurysm so as to provide some theoretical guidance for preoperative clinical decision-making in the future.
Methods: Four ideal geometric models were established for numerical computation: case 1 refers to an aneurysm without the use of stents, case 2 represents the implantation of two MSs in an aneurysm, and case 3 (SG + MS) and case 4 (MS + SG) both involve the treatment of an aneurysm by using a combination of SG and MG.
Results: The aneurysm pressure is slightly lower and there are more vortices when the SG is implanted (case 3 and case 4). In particular, for case 4, additional vortices appear in the sac and the area of the low-wall shear stress is larger on the aneurysm compared with those of the other three cases. However, the pressure becomes uneven, and a peak pressure region is observed on the wall of the aneurysm, and therefore, the aneurysmal wall will become buckled. In addition, the flux of the renal artery in the four cases is greater than that in the normal case.
Conclusion: The arrangements in cases 3 and 4 can effectively isolate the aneurysm from circulation, but clinically, it is necessary to avoid such a high-risk situation wherein the SG is positioned downstream of the aneurysm (case 4), even though this leads to improved isolation.

1. Background

An aneurysm is a serious condition that endangers a patient's life; it continues to grow until it eventually ruptures and patients with this condition have a mortality rate of 70–95%, unless it is treated in time (Gasser et al., 2010; Xiong et al., 2016). According to statistics, approximately 150,000 patients are diagnosed with an aneurysm every year (Vorp and Vande Geest, 2005), and most of these patients include the elderly (Sakalihasan et al., 2005). Given the rate at which global aging is progressing, this situation may worsen. However, the advent of stent technology brings new hope for the treatment of aneurysms. Blum et al. (1997) treated an abdominal aorta aneurysm by using a stent graft (SG, a metal stent covered by dacron) in a clinical trial and found that the SG could effectively isolate the aneurysm from circulation, thereby preventing the aneurysm from expanding. Mitchell (1997) followed up with 44 thoracic aortic aneurysm patients, who were treated with an SG for an average of 12.6 months, with immediate thrombosis achieved in 36 patients and late thrombosis achieved in three patients. Ehrlich et al. (1998) found that SG treatment had a lower 30-day mortality rate than those of conventional treatment methods (profound hypothermic circulatory arrest, left heart bypass, and femoral nonheparinized roller pump), and the probability of complete thrombosis of the thoracic aortic aneurysm surrounding the SG was 80%. Back pain experienced by a 73-year-old hepatic aneurysm patient was resolved after receiving an SG implant by Larson et al. (2002). Another approach that has gradually been recognized for the treatment of aneurysm is the use of a multilayer stent (MS,a denser stent with multiple single-layer metal stents overlapped with each other). Henry et al. (2008) treated a 78-year-old aneurysm patient by using an MS, and, angiography showed that the aneurysm wall had completely shrunk six months after the operation. Balderi et al. (2013) followed up with five aneurysm patients who were treated with MSs for 24 months and found that the size of the aneurysm shrunk at an average rate of 23%. Zhang et al. (Peng et al., 2015; Zhang et al., 2014) and Xiong et al. (2016) conducted research on

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the hemodynamics of an aneurysm treated by an implanted MS and concluded that the pressure in the aneurysm became more uniform and the area of the low wall shear stress (WSS) was enlarged; these conditions are favorable to induce aneurysm thrombosis with MS intervention.

Both SG and MS are commonly used for the treatment of an aneurysm; they have different stiffnesses: an SG is an intact tube that ensures better isolation, and an MS is a porous mesh that keeps the branch vessel unobstructed. However, both these approaches have some limitations. In the case of a juxtarenal aortic aneurysm (JRAA), which involves important branches such as a renal artery, a more complex chimney technique for the SG (Bruen et al., 2011; Coscas et al., 2011; Katsargyris et al., 2013; Tricarico et al., 2017) is needed, and this requires complicated surgery. With respect to the MS, it is difficult to decide how many layers of the stent are optimal for JRAA owing to the complex geometric configuration. Especially, it is difficult to generate meshes when the number of stent layers is greater than three. Therefore, a new approach to treat an aneurysm is required. This led us to consider whether it would be possible to use a combination of MS and SG to exploit the advantages of both these techniques. The blood would be able to seep through the pore of the MS to ensure that the branch remains unobstructed, and the SG could isolate the aneurysm from circulation. Thus, a combination of MS and SG may be a feasible way to treat JRAA. Currently, the West China Hospital of Sichuan University has adopted this therapy for the first time in clinical practice. However, the exact positioning of the stent continues to remain a question (SG + MS? or MS + SG?). We therefore decided to analyze the hemodynamics of an aneurysm by investigating the flow field pattern, pressure, WSS, and flux of the renal artery after implanting both these types of stents.

2. Method

2.1. Models

Four simplified models were established in SOLIDWORKS (version 16.0) as shown in Fig. 1(A), wherein the diameter of the abdominal aorta and renal artery were 25 mm and 6 mm (Javadzadegan et al., 2016; Lee and Chen, 2002; Yu et al., 1999), respectively. The aorta axis and renal axis formed an angle of 45° in the same plane. We selected four fusiform aneurysms in this research, and the lengths of their long and short axes were 55 mm and 50 mm, respectively (Yu et al., 1999). In addition, the two-dimensional shape of the MS element with a thickness of approximately 0.2 mm is depicted in Fig. 1(C).

2.2. Grids

The grids (Fig. 2) were generated by ICEM (ANSYS, version 16.0). Tetrahedron grids were selected because they allow for an intricate geometry with a higher density of grids in sensitive places, such as along the vascular wall. In our study, the grids in case 1 included 242,406 cells; case 2 included 4,442,218 cells; case 3 included 5,123,263 cells; and case 4 included 5,225,274 cells. The command "grid adaption" was used to verify grid independence.

2.3. Assumption

Blood was assumed to behave as an incompressible Newtonian fluid (Ku, 1997; Wen et al., 2015), its density and viscosity being 1050 kg/cm^3 and 0.0035 kg/m·s^{-1}, respectively (Coppola and Caro, 2008; Wen et al., 2011). The surface of the stents and vessel wall were defined as having rigid and non-slip properties (Wen et al., 2015), because Leung et al. found that including fluid flow can change the local wall stress slightly. The effect becomes negligible as the difference between static structural and fluid structure interaction models is less than 1% (Leung et al., 2006). The existing thrombus in the sac before stent implantation was not considered because of the large differences among individual cases. The oscillation of time was ignored, as in most studies, and simulation was performed under steady conditions in this study (Ko et al., 2007; Politis et al., 2007; Yan et al., 2017).

2.4. Governing equations

The simulation was based on the three-dimensional incompressible Navier–Stokes equation and the continuity equation as follows:

$$\rho(\vec{u}\cdot\nabla)\vec{u} + \nabla p - \mu\Delta\vec{u} = 0 \quad (1)$$

$$\nabla\cdot\vec{u} = 0 \quad (2)$$

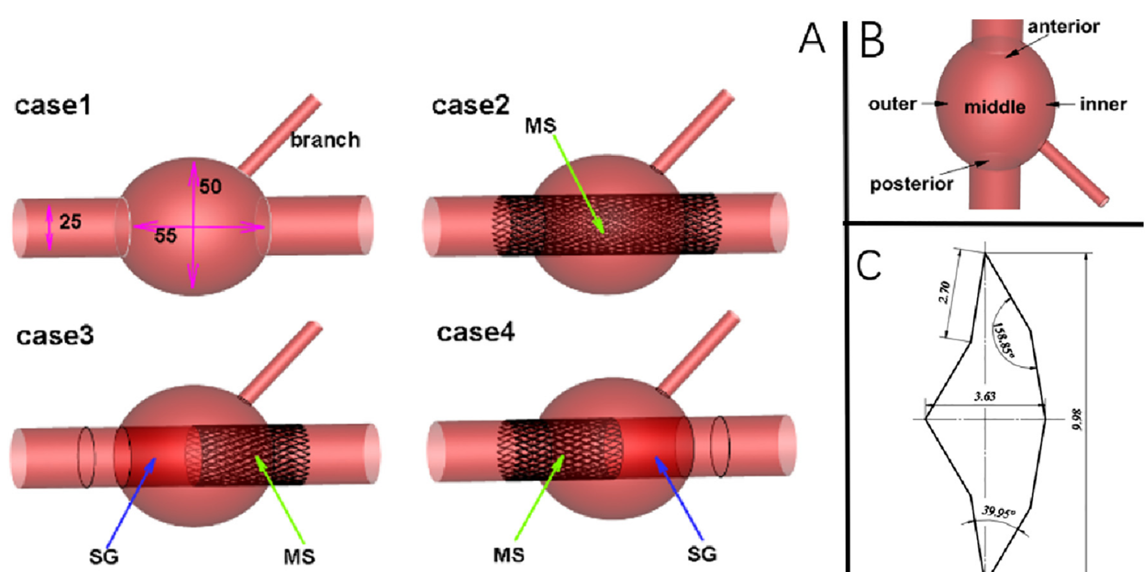

Fig. 1. Models used in our analysis. A presents four simplified cases of an aneurysm: case 1 corresponds to an aneurysm without a stent, case 2 corresponds to an aneurysm treated with MS, and in both case 3 (SG + MS) and case 4 (MS + SG), an aneurysm is treated with a combination of SG and MS; B shows the location and terminology used to describe an aneurysm; C depicts the two-dimensional configuration of the MS element (Sinus-XL, Optimed, Germany), which has a thickness of approximately 0.2 mm.