Journal of Biomechanics 47 (2014) 3524–3530

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Hemodynamic study of overlapping bare-metal stents intervention to aortic aneurysm

Peng Zhang [a], Anqiang Sun [a,*], Fan Zhan [a], Jingyuan Luan [b], Xiaoyan Deng [a,*]

[a] *Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China*
[b] *Department of Interventional Radiology and Vascular Surgery, Peking University Third Hospital, North Garden Road 49, Haidian District, Beijing 100191, China*

ARTICLE INFO

Article history:
Accepted 22 August 2014

Keywords:
Thoracic aortic aneurysm
Overlapping bare-metal stents
Hemodynamics
Numerical simulation

ABSTRACT

To investigate the hemodynamic performance of overlapping bare-metal stents intervention treatment to thoracic aortic aneurysms (TAA), three simplified TAA models, representing, no stent, with a single stent and 2 overlapped stents deployed in the aneurismal sac, were studied and compared in terms of flow velocity, wall shear stress (WSS) and pressure distributions by means of computational fluid dynamics. The results showed that overlapping stents intervention induced a flow field of slow velocity near the aneurismal wall. Single stent deployment in the sac reduced the jet-like flow formed prior to the proximal neck of the aneurysm, which impinged on the internal wall of the aneurysm. This jet-like flow vanished completely in the overlapping double stents case. Overlapping stents intervention led to an evident decrease in WSS; meanwhile, the pressure acting on the wall of the aneurysm was reduced slightly and presented more uniform distribution. The results therefore indicated that overlapping stents intervention may effectively isolate the thoracic aortic aneurysm, protecting it from rupture. In conclusion, overlapping bare-metal stents may serve a purpose similar to that of the multilayer aneurysm repair system (MARS) manufactured by Cardiatis SA (Isnes, Belgium).

1. Introduction

Endovascular aneurysm repair (EVAR) is now a widely practiced and relatively safe procedure for the treatment of thoracic and abdominal aortic aneurysms (Jackson et al., 2012; Katzen et al., 2005; Makaroun et al., 2008). Nevertheless, the EVAR procedure with stent-graft is not suitable for those aneurysms that have major arterial branches attached or located in the vicinity of the aneurismal necks, because the blood flow of the branches may be hindered by stent-grafts (de Beaufort et al., 2014; Henry et al., 2008).

To solve this, a novel aneurismal intervention device called multilayer aneurysm repair system (MARS) has been developed, which is manufactured by Cardiatis SA (Isnes, Belgium). Clinical trials have shown that when in place, the MARS can lead to a noticeable reduction in blood flow velocity in the aneurismal sac (Balderi et al., 2010, 2013; Benjelloun et al., 2012; Carrafiello et al., 2011; Henry et al., 2008), and hence induce an organized thrombus there that lessens the wall stress of the aneurysm protecting it from rupture effectively (Benjelloun et al., 2012; Borghi et al., 2008; Carrafiello et al., 2011; Henry et al., 2008; Vaislic et al., 2014).

However, the MARS is of high cost and is currently still in clinical trials. Since a variety of bare-metal stents' are widely used in vascular interventional treatments, it has been proposed by some researchers that if overlapped, bare-metal stents' might serve a similar purpose to that of the MARS. Several clinical trials using overlapping bare-metal stents' (Wallstent^{TM}, Boston Scientific Corp., Natick, MA) have been carried out to treat aortic aneurysms in Peking University Third Hospital, China (unpublished data, personal communication). At the three-month follow-up visit of the patients treated with overlapping bare-metal stents' in this hospital, computed tomography (CT) scans have shown stable thrombus in the aneurismal sac and regression of the aneurysms.

Until today, few studies have been reported that investigated the mechanism of aneurysm repair by means of the MARS or overlapping bare-metal stents' strategy. To further understand this treatment option, it is worth studying the hemodynamics within the aneurismal sac before and after stenting, instead of relying on *in vitro* or *in vivo* experiments merely.

Therefore, the present study is designed to evaluate the hemodynamic performance of this treatment using the computational fluid dynamics (CFD) method. To this end, simplified TAA

* Corresponding authors. Tel.: +86 10 82339962; fax: +86 10 82339428.
E-mail addresses: saq@buaa.edu.cn (A. Sun), dengxy1953@buaa.edu.cn (X. Deng).

http://dx.doi.org/10.1016/j.jbiomech.2014.08.025
0021-9290/

models in 3 cases, representing no stent, with a single stent and with double stents overlapped, were constructed and compared numerically in terms of flow velocity, wall shear stress (WSS) and pressure distributions.

2. Methods

2.1. Geometry

Three simplified 3-D models of thoracic aortic aneurysm were constructed using the commercial software Solid Works (Solid Works Corp, Concord, MA), and named Case 1, Case 2 and Case 3 (Fig. 1). The parameters of the aorta models referred to Liu's description (Liu et al., 2009). The diameters of inlet and outlet of the aorta were 25 mm and 17 mm (Liu et al., 2009). A typical aneurysm was created at the descending aorta with the maximum diameter of 40 mm (Case 1). One single stent and double stents overlapped were denoted as Case 2 and Case 3, respectively.

The stents' have a total length of $l=70$ mm and 20 wires with 1 mm diameter circular cross-section, which are fixed to the proximal and distal necks of the aneurysm. The outer stent was assumed to have half of its thickness embedded into the vessel wall according to the studies by coherence tomography observation (Tanigawa et al., 2007) and the inner stent was of a smaller diameter inserting into the outer stent. Spatially, the meshes of the two stents' were staggered completely, with every junction of one stent wire in the centre of the other stent mesh. The stents' covered the aneurismal segment completely and the stent axis was defined to be coincident with that of the aorta.

2.2. Meshing

Computational meshes in the three models were carried out using ANSYS ICEM CFD (ANSYS Inc., Canonsburg, PA). Case 1 model with no stent was meshed with only hexahedral elements, applying high quality boundary layers near the vessel wall. In order to reduce the computational expenditure, a hybrid discretization method (Chiastra et al., 2013) was applied to Cases 2 and 3, in which both tetrahedral and hexahedral elements were used.

In this study, high density mesh elements were applied close to stents and aneurismal vascular walls, in sizes of 0.1 mm and 0.5 mm respectively. The final volumes of the meshes were 191,268 cells for Case 1, whereas they were 2,957,879 cells and 4,157,954 cells, respectively, for Case 2 and Case 3.

2.3. Numerical approaches

2.3.1. Assumptions

Flow simulation under steady condition was performed in the present study. Blood was assumed as an incompressible, laminar, Newtonian fluid (Gao et al., 2013; Sun et al., 2010). Its density and viscosity were considered as constant with a value of 1050 kg/m^3 and 0.0035 Pa s, respectively (Liu et al., 2009). Vessel walls and all the stent surfaces were defined as rigid and no-slip.

2.3.2. Governing equations

The numerical simulation was based on the three-dimensional incompressible Navier–Stokes equations, which can be expressed as follows:

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

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

where $\vec{u}$ and p represent, respectively, the fluid velocity vector and the pressure, ρ and μ denote the density and dynamical viscosity of blood; ∇ is gradient symbol.

2.3.3. Boundary conditions

At the inlet section, a flat velocity profile was used with the time-averaged velocity of 0.1 m/s (Reynolds number 750) according to measurements (Hope et al., 2007; Liu et al., 2009). The assumption for a flat inlet velocity profile could be justified by the *in vivo* measurements and three-directional magnetic resonance velocity mapping of a patient, which indicated that blood flow at aorta inlet was flat with a weak helical component (Kilner et al., 1993; Morbiducci et al., 2013; Nerem, 1992). A fully developed flow (a zero diffusion flux for all flow variables) boundary condition was applied at the outlet section (Morbiducci et al., 2010).

2.3.4. Computation

CFD simulations were conducted using the commercial finite volume solver, ANSYS FLUENT CFD (ANSYS Inc., Canonsburg, PA). A pressure-based solver was used with a second-order up wind scheme for the momentum spatial discretization. Pressure was solved through the pressure–velocity coupling method known as the SIMPLE algorithm. Convergence criterion was set to 10^{-5} for continuity and 10^{-6} for velocity residuals. Parallel calculation was used in this study using a computer equipped with a 3.40 GHz quad-core processor with 8 GB RAM.

2.3.5. Statistical analysis

In order to present a quantitative description of WSS and pressure distribution, the area-weighted average of a quantity was used for the data analysis, and can be defined as

$$\frac{1}{A}\int \phi\, dA=\frac{1}{A}\sum_{i=1}^{n}\phi_i|A_i| \quad (3)$$

where ϕ represents the selected field variable, and A is the area value.

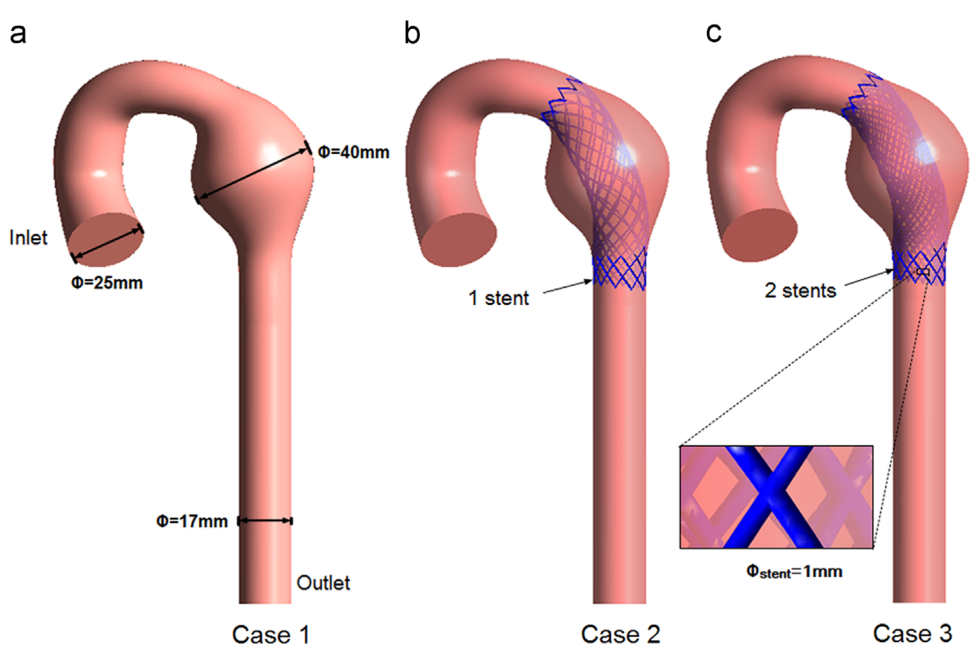

Fig. 1. The schematic representation of three aneurysm models: (a) Case 1 is the aneurysm geometry without stent; (b) Case 2 is the aneurysm geometry with a single stent; and (c) Case 3 is the aneurysm geometry with overlapping double stents.