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Approaches for treatment of aortic arch aneurysm, a numerical study

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ABSTRACT

Aortic arch aneurysm is a complex pathology which requires coverage of one or more aortic arch vessels. In this study we explore the hemodynamic behavior of the aortic arch in aneurysmatic and treated cases with three currently available treatment approaches: Surgery Graft, hybrid Stent-Graft and chimney Stent Graft. The analysis included four models of the time-dependent fluid domains of aneurysmatic arch and of the surgery, hybrid and chimney endovascular techniques. Dimensions of the models are based on typical anatomy, and boundary conditions are based on typical physiological flow.

The simulations used computational fluid dynamics (CFD) methods to delineate the time-dependent flow dynamics in the four geometric models.

Results of velocity vectors, flow patterns, blood pressure and wall shear stress distributions are presented.

The results delineate disturbed and recirculating flow in the aortic arch aneurysm accompanied with low wall shear stress and velocities, compared to a uniformly directed flow and nominal wall shear stress (WSS) in the model of Surgery graft. Out of the two endograft procedures, the hybrid procedure clearly exhibits better hemodynamic performances over the chimney model, with lower WSS, lower pressure drop and less disturbed and vortical flow regions. Although the chimney procedure requires less manufacturing time and cost, it is associated with higher risk rates, and therefore, it is recommended only for emergency cases. This study may shed light on the hemodynamic factors for these complications and provide insight into ways to improve the procedure.

1. Introduction

Aortic arch aneurysm is a rare condition but carries a high risk of rupture. It enlarges faster and has a higher risk of rupture than other aneurysms. Aneurysmal disease that involves the entire aortic arch is especially prone to extensive involvement because it is a result of diffuse aortic dissection or medial degenerative disease in most cases (Patel and Deeb, 2008). The actuarial 5-year survival of untreated patients is only 13% with many patients dying from aortic rupture. Other severe complications are related to formation of intraluminal thrombus and calcification, which might lead to strokes (Xenos and Bluestein, 2011; Kawatani et al., 2015).

The traditional treatment of aortic arch replacement via open-chest surgery (Fig. 1b) is a highly complex operation which carries a substantial risk of morbidity and mortality. It requires cardiopulmonary bypass and periods of profound hypothermic circulatory arrest for limiting cerebral metabolism (Ziganshin and Elefteriades, 2013; Al Kindi et al., 2014). Recent advances in imaging technology and materials technology introduce the endovascular stent graft technology for treatment of aortic pathologies. The use of endovascular stent grafting for repair of aortic aneurysm offers distinct advantages over conventional open surgery as it is deployed under a minimally invasive procedure and without interrupting blood flow. Therefore, it has the potential benefits of greatly reduced risk, a shorter hospital stay, and a more rapid recovery. It is associated with a lower mortality rate, and better short-term performance outcomes (Makaroun et al., 2008; Naughton et al., 2012; Kawatani et al., 2015; Martin et al., 2016).

However, the major challenge in endovascular repair of the aortic arch, as in surgical repair, is to maintain blood flow to the brain and side branches in the sealing zone of the stent-graft (Criado et al., 2002). Several approaches were introduced to overcome this challenge. The main two approaches considered are the *total hybrid debranching procedures* (see Fig. 1c), and the graft procedures using fenestrations or chimney technique (e.g. *Chimney of innominate artery*, see Fig. 1d). The hybrid total aortic arch debranching (Buth et al., 1998; Gottardi et al., 2005; Saleh and Inglese, 2006; Brinkman et al., 2007) is a combined open heart and endovascular procedure. A bifurcated Dacron graft is connected to the ascending aorta using a proximal end-to-side anastomosis. The

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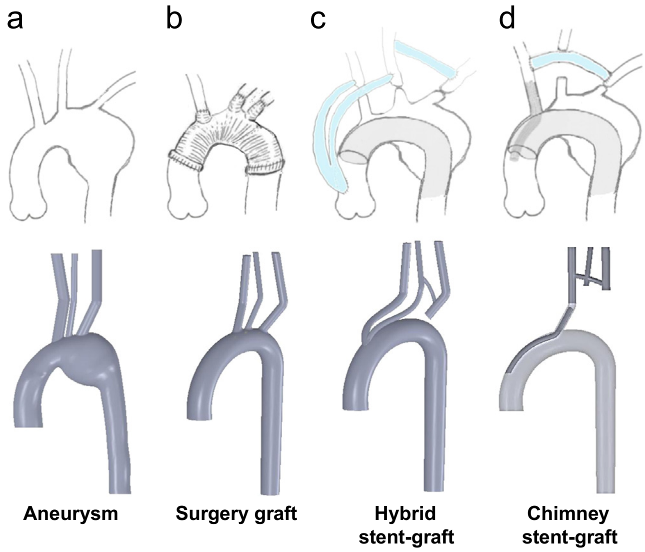

Fig. 1. Schematic illustrations and the geometrical models of the four models: (a) aneurysmatic aortic arch, (b) surgery graft, (c) hybrid graft and (d) chimney stent-graft procedures.

deployment of the endograft is done after bypassing the LSA as shown in Fig. 1c. The graft is custom made in order to minimize interference with the aortic valve and left artery, and thus to fit each individual patient. Although this method requires open surgery to perform the debranching of the supra-aortic vessels, it is considered less invasive and risky when compared to open-chest surgical repair since there is no need for profound hypothermic cardiac arrest (Antoniou et al., 2010; Shirakawa et al., 2013; Zerwes et al., 2015).

In the chimney graft technique (Baldwin et al., 2008; Ohrlander et al., 2008; Cires et al., 2011; Moulakakis et al., 2013), a covered stent is deployed parallel to the main aortic stent-graft, protruding somewhat proximally, like a chimney, to preserve flow to a vital side branch, e.g. the Innominate artery (IA), or the left Subclavian artery (LSA). This technique requires *two* bypass connections between the side branches; e.g., bypass between the IA and the LSA and between the LSA and the left common carotid artery (LCCA), as shown in Fig. 1d. The chimney graft technique allows the use of standard off-the-shelf stent-grafts to instantly treat lesions in aneurysms with challenging neck morphology, providing an alternative to fenestrated stent-grafts in urgent cases. The advantage of chimney repair compared to the other two methods is clear: the stent graft is put into place without open-chest surgery. However, it requires two bypass connections and the entire flow to the upper vessels depends on the single endograft, which is not designed specifically for the anatomic or physiologic conditions found in the arch and its long-term durability remains in question (Yang et al., 2012; Moulakakis et al., 2013).

Both endovascular approaches were proven to be technically feasible with high short-term technical success rate and relatively favorable rates of perioperative outcomes (Melissano et al., 2007; Antoniou et al., 2010; Bavaria et al., 2013). Long-term outcomes remain undefined (Szeto et al., 2007; Cires et al., 2011; Yang et al., 2012, Moulakakis et al., 2013; Benrashid et al., 2016). The hybrid technique is considered to have better performance; however it uses custom-made devices associated with long manufacturing times and increased costs (Yoshida et al., 2011; Martin et al., 2016) and is associated with a high reintervention rate due to stent-graft–related complications including migration, endoleaks, stent-graft collapse or fracture, new entry tears or aortic dissection and false lumen thrombosis (Nauta et al., 2015; Benrashid et al., 2016). The chimney technique has the advantage of applying available off-the-shelf devices, being technically less complex. In high-risk patients, however, this technique is associated with a relevant morbidity, mortality, and reintervention rate. Therefore, it is often recommended only for patients not suitable for conventional aortic arch repair or emergency cases (Sugiura et al., 2009; Geisbüsch et al., 2011).

Blood hemodynamics in the vascular domain has a major role in the disease progression or treatment success. Aneurysmal growth and rupture are strongly correlated with both low and high Wall Shear Stress (WSS) (Feliciani et al., 2015). Vascular regions with disturbed flow accompanied by turbulent flow, low, oscillatory or instantaneous negative WSS and high WSS gradients are strongly correlated with vascular pathologies, cardiovascular diseases, thrombus formation and calcification (Einav and Bluestein, 2004; Reneman et al., 2006; Davies, 2009; Rissland et al., 2009; Tarbell et al., 2014; Zhang et al., 2015). Pressure-related forces are determining factors of drag forces on the stent-grafts leading to stent migration and branches endoleaks or stenosis are often correlated to flow disturbances and small scale vortices in the arterial bypasses (Avrahami et al., 2012). In addition, high velocities have been identified at the stent-graft–induced stenosis of the branches and the distal descending aorta (Wentzel et al., 2005; Canstein et al., 2008; Midulla et al., 2012; van Bogerijen et al., 2014; Nauta et al., 2015). Therefore, a better understanding of the hemodynamic aspects of the different approaches may shed some light on the advantages or complications of each procedure.

Computational fluid dynamics (CFD) has been excessively used as a useful tool for exploring of the complex flow mechanics in the aortic arch aneurysm and various treatment approaches in the aortic arch. It was used to analyses and compare the flow patterns, pressure gradients and WSS distribution in the aortic arch, using different flow conditions (Shahcheraghi et al., 2002; Morris et al., 2005; Liu et al., 2009a, 2009b; Liu et al., 2011; Tse et al., 2011; Avrahami, 2013; Avrahami et al., 2013; Markl et al., 2016) before and after treatment for patient specific procedures (Shahcheraghi et al., 2002; Morris et al., 2005; Figueroa et al., 2009; Liu et al., 2009a, 2009b; Tan et al., 2009; Liu et al., 2011; Midulla et al., 2012; Vasava et al., 2012; Konoura et al., 2013; van Bogerijen et al., 2014; Markl et al., 2016) and to analyze drag forces acting on the graft (Lam et al., 2008; Liu et al., 2015).

Previous computational studies addressed mostly the fluid dynamics in the aneurysm sac before and after stent grafting, and only few of them addresses chimney endograft procedures. To our knowledge, no investigation was conducted to compare the different endograft approaches from engineering point of view. In this study we use numerical methods to explore and compare the hemodynamic behavior of the aortic arch for aneurysmatic and for these three treatment approaches.

2. Methods

The analysis included four models of the time-dependent fluid domains of aneurysmatic arch and of the surgery, hybrid and chimney endovascular techniques (Fig. 1).

The flow and pressure fields in the lumen were calculated by numerically solving the momentum and continuity equations for incompressible and Newtonian fluid:

$$\nabla\cdot\mathbf{V}=0\rho\frac{D\mathbf{V}}{Dt}=-\nabla p+\mu\nabla^2\mathbf{V}+\rho\mathbf{g} \qquad (1)$$

where p is static pressure, t is time, V is the velocity vector, ρ and μ are density and dynamic viscosity of blood, respectively, and g is the gravity vector. Blood was assumed homogenous, incompressible (with $\rho=1$ gr/mL), and Newtonian (with $\mu=3.5$ cP), and a gravity of $g=981$ cm/s^2 was employed. Flow was assumed laminar. No slip and no penetration boundary conditions were imposed at the grafts and vessels walls ($V_t=V_n=0$). At the aortic inlet, boundary conditions were set according to typical physiological conditions with pulsatile pressure of 120/80 mmHg, a heart rate of 75 BPM, and an average cardiac output of CO=5 L/min