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A computational exploration of helical arterio-venous graft designs

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ABSTRACT

Although arterio-venous grafts (AVGs) are the second best option as long-term vascular access for hemodialysis, they suffer from complications caused by intimal hyperplasia, mainly located in vessel regions of low and oscillating wall shear stress. However, certain flow patterns in the bulk may reduce these unfavorable hemodynamic conditions. We therefore studied, with computational fluid dynamics (CFD), the impact of a helical AVG design on the occurrence of (un)favorable hemodynamic conditions at the venous anastomosis.

Six CFD-models of an AVG in closed-loop configuration were constructed: one conventional straight graft, and five helical designed grafts with a pitch of 105 mm down to 35 mm. At the venous anastomosis, disturbed shear was assessed by quantifying the area with unfavorable conditions, and by analyzing averaged values in a case-specific patch. The bulk hemodynamics were assessed by analyzing the kinetic helicity in and the pressure drop over the graft.

The most helical design scores best, being instrumental to suppress disturbed shear in the venous segment. There is, however, no trivial relationship between the number of helix turns of the graft and disturbed shear in the venous segment, when a realistic closed-loop AVG model is investigated. Bulk flow investigation showed a marked increase of helicity intensity in, and a moderate pressure drop over the AVG by introducing a lower pitch.

At the venous anastomosis, unfavorable hemodynamic conditions can be reduced by introducing a helical design. However, due to the complex flow conditions, the optimal helical design for an AVG cannot be derived without studying case by case.

1. Introduction

Nowadays, over 20 million patients worldwide are in need of renal replacement therapy (Grassmann et al., 2005, 2006). In western countries, over 90% of the patients waiting for a kidney transplant depend on hemodialysis (ERA-EDTA, 2011; USRDS, 2010), and need a long-term vascular access. Although an arterio-venous fistula (AVF) is the first choice in most patients, in specific cases (e.g. low quality vessels in elderly or diabetics) an arterio-venous graft (AVG) is the second best option (Scott and Glickman, 2007). Hereby an artery and a vein, mostly in the (lower) arm are connected by a synthetic graft.

AVGs, however, deal with complications such as thrombosis and stenosis formation. As clinically observed, the stenosis formation with AVGs is mainly located at the venous anastomosis or in the draining vein (Allon, 2007; Loth et al., 2008; Roy-Chaudhury et al., 2006). These adverse events, due to maladapted intimal hyperplasia (IH) (Allon, 2007; Hodges et al., 1997), are driven by abnormal hemodynamics. It is known from literature that, after vascular access creation, the flow field may play a modulating role, with IH mainly located in regions of low wall shear stress, high oscillatory shear stress and high residence time (Loth et al., 2008; Roy-Chaudhury et al., 2006, 2007; Himburg et al., 2004; Lee et al., 2009; Rittgers et al., 1978; Zhuang et al., 1998; Sherwin et al., 1998). Furthermore, certain flow patterns in the bulk, induced by out-of-plane geometries, can be linked to disturbed shear distributions at the luminal surface (Caro et al., 1996; Sherwin et al., 2000; Coppola and Caro, 2009; Papaharilaou et al., 2002). More specifically, helical flow tends to reduce these unfavorable hemodynamic conditions (Grigioni et al., 2005; Morbiducci et al., 2010, 2007, 2011b; Zhan et al., 2010).

With this in mind, a helical shape was introduced in AVG designs by Caro et al. (2007, 2005). Up to now, the research on helical AVGs as vascular access consists of an animal model study (Caro et al., 2005), a preliminary clinical study on 20 patients (Huijbregts et al., 2007), and a clinical trial on 180 patients, as suggested in the work by Glickman (2009). In other studies,

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computational fluid dynamics (CFD) was applied to analyze the hemodynamic performances of helical grafts in a stand-alone (Sun et al., 2010; Zheng et al., 2009) and in a bypass configuration (Wen et al., 2011), not only to minimize disturbed shear but also to improve near wall and central flow mixing. Sun et al. (2010) compared the helical graft design from Caro et al. (2005) with a new helical design, using steady-state flow conditions. Cookson et al. (2009) investigated the in-plane flow structures and central flow mixing in helical conduits in steady-state flow conditions. Coppola and Caro (2009) investigated the impact of arterial three-dimensionality on both wall shear stress and oxygen transport/transfer. Zheng et al. (2009) simulated steady flows in helical grafts and carried out a parametric analysis with respect to the Dean number and helical pipe geometric features, i.e. helical pitch and amplitude. Recently, Zheng et al. (2012) simulated the physiological pulsatile flow in helical grafts and observed that helical geometry creates amplified WSS magnitudes near the wall, that oscillatory shear never exceeds non-physiologically significant values, and that the strong secondary flows improve flow mixing between low-momentum fluid near the surface and high-momentum fluid near the central flow. Only Wen et al. (2011) studied the graft in a coronary bypass setup (low flow, small diameter, no loop) and one helical design was compared to the straight conventional design. So, while different computational studies have been performed in low flow (coronary) bypass configurations or in stand-alone configurations without (arterial or venous) anastomosis, up till now, the clinically relevant, high flow, helically designed loop AVG configuration has not been studied in detail (Loth et al., 2008).

Therefore, the aim of this study was to investigate, using CFD, the impact of the introduction of helical design in an AVG loop as a vascular access for hemodialysis on the occurrence of (un)favorable hemodynamic conditions at the venous anastomosis (Allon, 2007; Loth et al., 2008; Roy-Chaudhury et al., 2006).

2. Materials and methods

Six different parametric models of a graft connecting an artery and a vein were created in pyFormex (http://pyformex.org). All models consist of a 4 mm (diameter) artery, a 6 mm graft section and a 6 mm vein, as shown in Fig. 1. The graft section has a length of 300 mm in a loop configuration with both anastomosis angles set at 45°. As a reference model, a straight conventional graft (SCG) was constructed. As shown in Fig. 2, five helical design grafts (HDG-1 to HDG-5) were created to analyze the influence of a helical design on hemodynamics. The amplitude of the helix of the graft was 3 mm (half the graft's diameter) and one helix turn (pitch) was 105 mm, 87.5 mm, 70 mm, 52.5 mm or 35 mm long, respectively. HDG-3 is based on the design of the SwirlGraft (Veryan Medical Limited, UK).

The models were discretized with a fully conformal and structured hexahedral mesh (De Santis et al., 2010, 2011a,b). Because of the high flow rates and the expected transitional flow patterns (Lee et al., 2007), an extensive mesh density and time step analysis was performed. 200 Hz sampling and consecutive mesh refinement up to 4.3 million cells (4.5 million nodes) resulted in WSS values at the venous anastomosis region within 2% of the results obtained with a 6.4 million cell model. With the used hexahedral meshed meshes, about 140 h, on 24 nodes of an in-house cluster, were required to calculate two consecutive cardiac cycles, for one model.

The finite volume method was applied to solve the laminar governing equations of the fluid motion, by use of the general purpose CFD code Ansys Fluent 12 (ANSYS Inc., Canonsburg, PA, USA).

A post-operative flow waveform from a vascular access patient was acquired by the use of magnetic resonance imaging as described by Huberts et al. (2012). A patient-specific flow waveform was set, in terms of parabolic velocity profile, as inlet boundary condition at the proximal artery (Fig. 1). The profile was scaled to achieve a time-averaged flow rate of 600 ml/min, which is in line with the European and American guidelines on vascular access (Tordoir et al., 2007; NKF-K/DOQI, 2006). The inflow was redistributed such that 95% was sent to the graft (with a further downstream division of 90% of to the proximal vein and 5% to the distal vein), and 5% to the distal artery. The flow split is in accordance with the American guidelines stating that the difference between the flow in the artery and the access is usually less than 10% (NKF-K/DOQI, 2006). Furthermore, a flow of 30 ml/min (absolute value) to the distal segments of the lower arm (hand) is a value well acceptable in clinical practice.

To mimic blood, a shear thinning fluid, defined by the Quemada viscosity model (Quemada, 1981) (1.3 mPa s plasma viscosity and 40% hematocrit) with a density of 1050 kg/m^3, was implemented, as suggested by Loth et al., (2008).

As for the computational setting, standard pressure discretization and second-order upwind momentum discretization schemes were applied. After a time step sensitivity analysis, a 5 ms time step was chosen and two cardiac cycles were calculated. In all cases, the analysis and post-processing was performed on the second time step using Matlab (The Mathworks, Natick, MA, USA) and Tecplot (Tecplot inc, Bellevue, WA, USA).

Three wall shear stress-based descriptors of the flow field were calculated in the region of interest (ROI) at the venous anastomosis (ROI-1, Fig. 1). The time-averaged wall shear stress (TAWSS) was calculated as the integral over time of the absolute value of the WSS-vector, with T representing one cardiac cycle

$$\mathrm{TAWSS} = \frac{1}{T}\int_0^T |\overline{\mathrm{WSS}}|\, \mathrm{d}t \tag{1}$$

To assess the change in direction of the flow and, with it, the velocity gradient during a cardiac cycle, the oscillatory shear index (OSI), originally introduced by

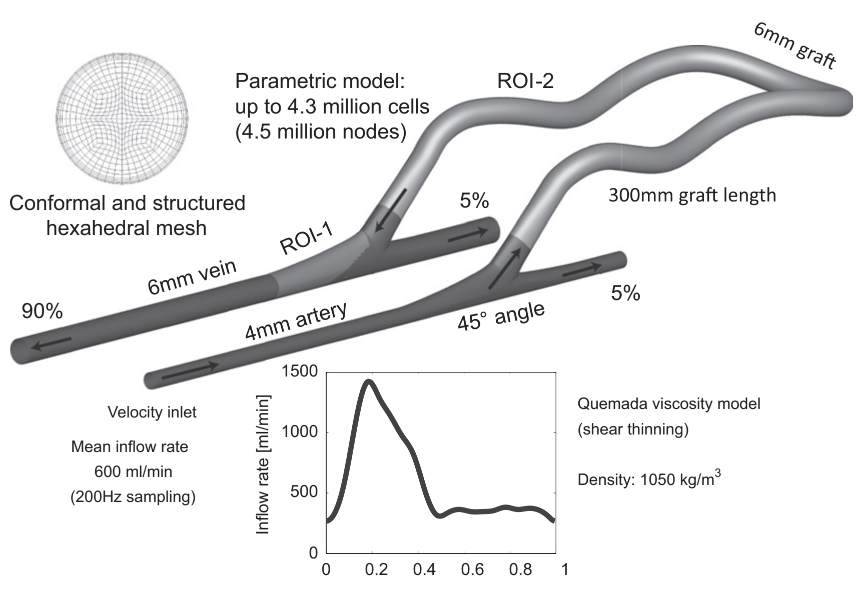

Fig. 1. Summary of model, mesh, material properties and boundary conditions (example of HDG-3). Region of interest at venous anastomosis site (ROI-1) and region of interest in graft section (ROI-2) are highlighted.