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Numerical investigation on the geometrical effects of novel graft designs for peripheral artery bypass surgery

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Abstract

The design of prosthetic grafts plays an essential role on the hemodynamics through the graft anastomosis. Research has shown that swirling flow, which is caused by the rotational compressive pumping of the heart, is a natural phenomenon in the arterial system and results in removing unfavourable flow environment. Recently, non-planar helical grafts have shown to perform better than grafts with internal spiral ridge in inducing the swirling flow. The present work investigates the importance of the ridge design and in particular, shows that the ridge trailing edge orientation at the anastomosis has significant effects in potentially improving the hemodynamic efficiency of this type of graft.

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Keywords: CFD; Biodesign; Hemodynamics; Spiral flow; Prosthetic graft; Bypass surgery.

1. Introduction

An anastomosis is a surgical connection between a natural or prosthetic graft and veins or arteries. Generally, the graft anastomoses can be divided into three configurations: (1) end-to-side, (2) end-to-end, and (3) side-to-side anastomosis.

Vascular graft anastomoses are currently used mainly as Arterial Bypass Grafts (ABGs). Examples of ABGs include peripheral arterial grafts and Coronary Artery Bypass Grafts (CABGs). Each year over a million vascular grafts (excluding valves) are used in current medical practice. Problems requiring the use of a graft include vessels occlusion, damaged vessels resulting from trauma or aneurysm, and the formation of a new tissue structure through regenerative therapies. In ABGs, currently, the ‘gold standard’ option is to use naturally occurring vessels (‘autologous’ grafts); however, this brings inherent problems including additional surgery for the patient, and the frequent unsuitability or limited availability of their vessels due to systemic disease. There is also a lack of viable treatment options when the blood vessel is less than 6 mm in diameter [1]. Hence, prosthetic grafts, following either biomaterial or tissue engineered approaches, are utilised. Current prosthetic surgical options commonly include Dacron (Polyethylene Terephthalate, PET) and expanded Polytetrafluoroethylene (ePTFE). Unfortunately, prosthetic grafts are known to exhibit unsatisfactory long-term performances [2]; therefore, much research is being performed to reduce failure rates and improve patency rates, particularly for vessels under 6 mm in diameter.

Graft failure is currently a major concern for medical practitioners in treating peripheral vascular disease (PVD) and coronary artery disease (CAD). Early graft failure (within 30 days) is attributable to surgical technical errors and resulting thrombosis, while late graft failures are mainly caused by progression of atherosclerosis and Intimal Hyperplasia (IH) [3,4]. It is now widely accepted that hemodynamic factors play a crucial role in the formation and development of IH [5,6].

To improve the efficiency of ABGs, several attempts have been made in the past few decades to mimic the physiological blood flow in arteries and grafts. Research has shown that the

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'spiral flow' is a natural phenomenon in the whole arterial system [7,8]; the rotational motion of the blood flow is induced by the twisting of the left ventricle during contraction and then accentuated upon entering the aortic arch [9]. In addition, the swirling flow has been identified as anticlockwise in the right common iliac arteries and clockwise in the left common iliac arteries [10,11]. Two of the most recent and innovative designs based on inducing spiral flow in grafts include: 1) *'SwirlGraft'* [12] which has a helical out-of-plane geometric feature incorporating 'Small Amplitude Helical Technology' (SMAHT), and 2) *'Spiral Flow Graft'* [13] which is engineered to induce spiral flow through an internal ridge within its distal end.

The aim of this study is to carry out a numerical investigation on the hemodynamic effects of different geometrical design parameters in swirl-inducing bypass grafts.

2. Method

2.1. Geometrical Models

The main geometry studied in this work represents a typical End-To-Side (ETS) distal graft anastomosis, which can be found in the following three graft configurations: 1) Peripheral Artery Bypass Graft, 2) Coronary Artery Bypass Graft, and 3) Arterio-Venous Access Graft. The former has been selected for the present work since both of the novel flow field augmentation designs discussed above, so far have only been tested for the peripheral artery bypass configuration.

Figure 1 shows the schematics of all the geometrical models tested in the present study.

2.2. Numerical Procedure

Mesh: The computational domains used for the present simulations were based on finite-volume hybrid mesh consisting of prismatic elements for the near-wall and tetrahedral elements for the core regions and were generated using ANSYS-Meshing (Version 14.5). In order to ensure the accuracy of the simulations, a series of steady-state computations with different mesh refinement were conducted to ensure grid independency prior to running the present computations.

Boundary conditions: The blood flow is assumed as three-dimensional, incompressible, isothermal and laminar. The Carreau-Yasuda model is used to describe the non-Newtonian rheology of the blood [15]. Constant and pulsatile flow rates are applied at the inlet for the different steady-state and transient cases, respectively. At the artery outlet, the traction-free outflow boundary condition is applied. Also, the no-slip boundary condition is applied to all walls. A rigid wall model is assumed in the present study, which has been shown to be a valid assumption [16,17].

Solver settings: The governing equations are solved numerically by a finite volume method and the CFD code, ANSYS CFX (Version 14.0), using a high resolution scheme in steady-state simulations and a fully implicit second-order backward Euler differencing scheme in transient simulations. For the latter, the time-step size is taken to be 0.01 s, and the results are recorded at the end of each time-step. In order to eliminate the start-up effects of transient flow, the computation is carried out for four periods, and the fourth period results are presented. The convergence criterion (a normalised residual, obtained based on the imbalance in the linearized system of discrete equations) is set to 10^{-6} in this study.

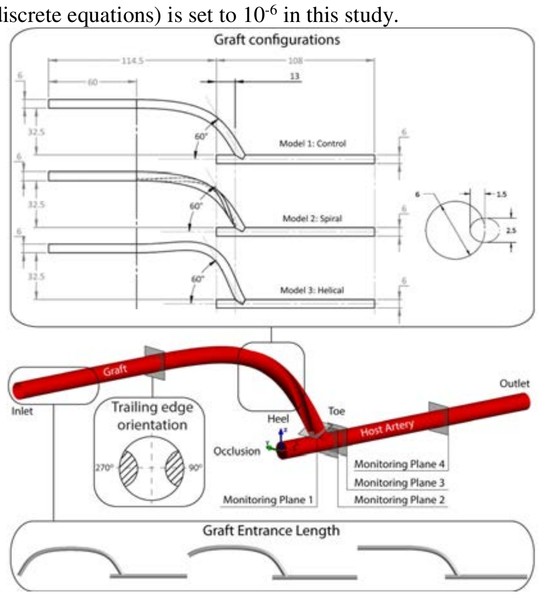

Figure 1 – Schematic of the computational models tested in the present work.

3. Results and Discussion

3.1. Validation Test

The spiral graft configuration was used in order to assess the accuracy of the computational method against the experimental results obtained by Kokkalis et al. [18]. Figure 2 compares the contours of normalised secondary velocity magnitude at monitoring plane 3 using the present numerical method under steady-state conditions with the experimental data using the Spiral Laminar Flow PV graft (Vascular Flow Technologies Ltd., Dundee, UK). The qualitative assessment of results enables to identify the weakest and strongest areas of secondary flow.

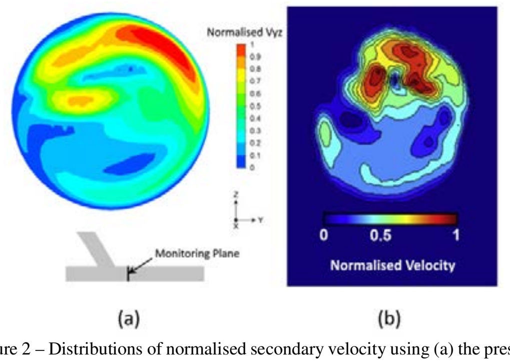

Figure 2 – Distributions of normalised secondary velocity using (a) the present numerical method and (b) experimental measurements of Kokkalis et al. [18] at monitoring plane 3 and Re=1140.