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A numerical study on steady flow in helically sinuous vascular prostheses

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ABSTRACT

The objective of the present study is to investigate flows in helically sinuous tubes with a small amplitude of helicity for physiological and clinical applications. Three-dimensional computations of steady flows in helically sinuous tubes are carried out by using a Navier–Stokes solver based on the spectral/hp element method for high accuracy. Results show that the flow fields are affected by the curvature and the torsion of the helically sinuous tube geometry in terms of axial velocity, axial vorticity and wall shear stress. The position of the maximum axial velocity is influenced more by the curvature than by the torsion. Most importantly, the torsion remarkably changes the Dean vortices produced by the curvature to a predominantly single vortex. Accordingly, it is proposed that the fluid dynamics knowledge gained from the present investigation can be utilized for the design of innovative prosthetic grafts that can control the biological reactivity of coagulant interacting with the prosthetic vascular surface or wall.

1. Introduction

Today, most industrialized countries suffer from high rates of atherosclerotic diseases. For treatment of vascular diseases, millions of medical prostheses such as vascular grafts, shunts and stents are implanted into humans each year. However, there are still failures of treatment due to clotting, thrombosis, intimal hyperplasia (IH), fibrosis and occlusions.

Once a prosthetic biomaterial (graft, shunt, stent, etc.) is implanted, it is treated by the body as an unrecognized foreign invader. Through an intrinsic pathway, proteins, platelets, white blood cells, red blood cells, etc. adhere and interact through crossed-linked fibrin, resulting in clots, fibrosis or collagen on the prosthesis surface or on the damaged vascular surface [1–3].

Coagulation, fibrosis and collagen sac reactions are frequently observed in prosthetic vessels. These responses to a foreign body are caused by the lack of endothelial cells on the surface of prostheses, whereas endothelial cells destroy coagulation factors V and VIII. Many attempts have been made to improve the patency of prostheses by applying a heparin or generating endothelial cells on the surface and so forth. In spite of these various efforts, vascular prostheses are still limited by poor bio-compatibility.

Indeed, there is still increased emphasis on overcoming these limitations by modifying other risk factors; thus it has been a long-standing challenge to identify fluid-dynamically influenced patterns of vascular diseases. Some researchers have applied the knowledge of hemodynamic mechanisms to the optimum design of expanded polytetrafluorethylene (ePTFE) grafts and shunts to prevent occlusions. In an animal test, Caro et al. [4] implanted a small-amplitude helical shunt in the left neck of a pig and a conventional straight shunt in the right neck of the same pig. It was reported that less thrombosis, fibrosis and IH occurred in the swirl-graft than in the conventional straight graft, as shown in Fig. 1 [4]. Later, the helical shunt was implanted in the arms of patients in a preliminary clinical study [5]. There was no great difference of the primary patency rates of grafts between patients treated by conventional grafts and those treated by helical grafts. However, higher assisted primary patency rates of grafts and higher secondary patency rates of grafts were reported for the patients treated by the helical grafts than for those treated by the conventional grafts [5]. Primary patency, assisted primary patency and secondary patency are defined most concisely in Ref. [6]. Primary patency of a bypass refers to the duration that the graft remains patent without any type of intervention, either surgical or percutaneous. Assisted primary patency refers to a graft that always remains patent but requires some sort of interventions, either surgical or percutaneous, to maintain adequate blood flow through it. Secondary patency refers to a graft that has thrombosed and has had patency restored with either thrombolytic therapy or operative thrombectomy. From the above-mentioned animal test and clinical study, optimization of the design of vascular prostheses (e.g., shunt, graft and stent) appears promising. However, there is still uncertainty about the correlation between the exact mechanism of the hemodynamics and the patency rates. The benefit of design opti-

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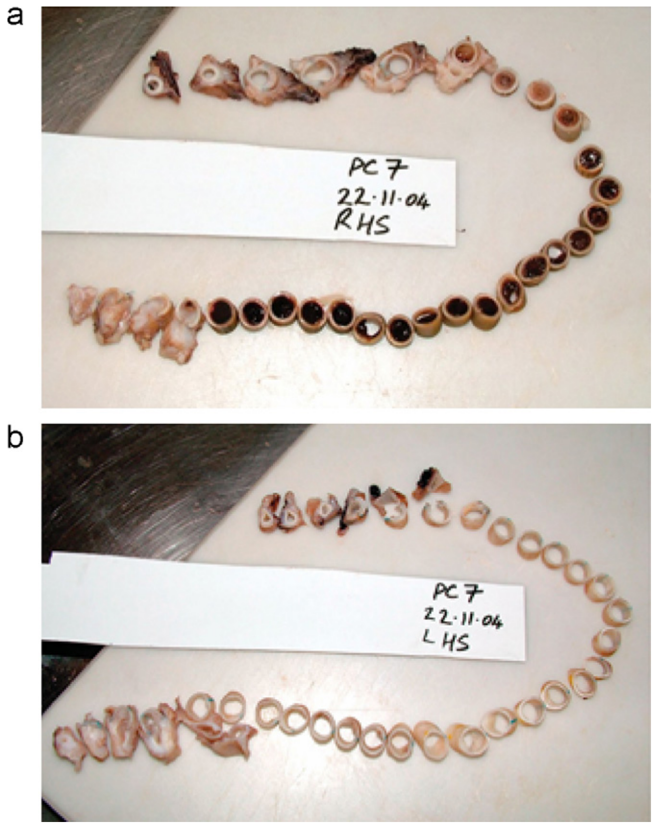

Fig. 1. (a) Thrombosis and intimal hyperplasia are observed in the conventional straight shunts implanted in the right neck of a pig, while (b) a helical swirlgraft implanted in the left neck of the same pig is relatively free of thrombosis and intimal hyperplasia.
This figure is a reproduction of Fig. 3 of Ref. [4], for which permission was granted by the publisher.

mization of vascular prostheses is explained by numerical studies in terms of hemodynamic factors, e.g., velocity, secondary motion, separation, wall shear stress and coherent vortical structure.

Starting with Wang's [7] non-orthogonal coordinate system and Germano's [8] orthogonal coordinate system, many fundamental studies have been carried out to investigate the effect of torsion and curvature on the flow in a helical pipe. Tuttle [9] used the frame of reference of an observer to state qualitatively the degree of the torsion effect on secondary flow. Zabielski and Mestel [10] suggested a helically symmetric co-ordinate system for computational efficiency. Liu and Masliyah [11] studied the effect of the geometric parameters on helical pipe flow in terms of the Dean number, normalized curvature ratio and normalized torsion. Wang and Andrews [12] provided a comprehensive study on the effects of the pitch ratio, curvature ratio and pressure gradient on helical flow, secondary flow and resistance of flow in helical ducts whose characteristic lengths are schematically shown in Fig. 2 where R, r and P are the radius of the helix, the radius of tube cross-section and the pitch of the helix, respectively. Geometric parameters such as amplitude [13], curvature and torsion [12] are given as follows:

$$\text{Amplitude}\,(A) = \frac{(W-2r)/2r}{2} \tag{1}$$

$$\text{Pitch ratio}\,(\alpha) = \frac{P}{R} \tag{2}$$

$$\text{Curvature}\,(\kappa) = \frac{R}{(P/2\pi)^2 + R^2} \tag{3}$$

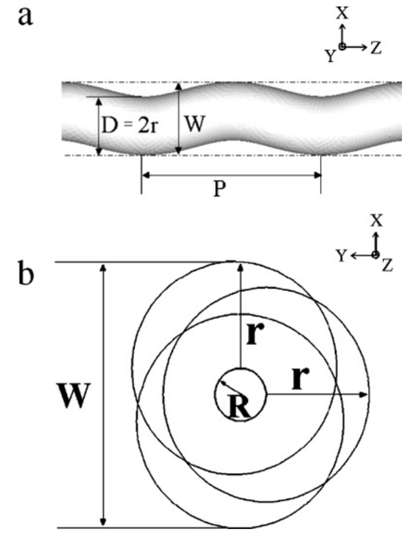

Fig. 2. (a) A side view and (b) a front view of a two-turn helix, where r, R and W are, respectively, the radius of the tube cross-section, the radius of the helix and the width of the helix.

$$\text{Dimensionless curvature}\,(\varepsilon) = \frac{R}{(P/2\pi)^2 + R^2} \times r \tag{4}$$

$$\text{Torsion}\,(\tau) = \frac{P/2\pi}{(P/2\pi)^2 + R^2} c \tag{5}$$

$$\text{Dimensionless torsion}\,(\lambda) = \frac{P/2\pi}{(P/2\pi)^2 + R^2} \times r \tag{6}$$

It was also reported that a single vortex was found instead of a pair of vortices, when $\alpha > 10$.

Recent studies consider the influence of cross-sectional configuration on the flow, with regard to a helical square duct, a tube with a circular cross-section having sinusoidal corrugations and a twisted tube [14–16]. Secondary flow patterns and the stability of flow in a helical pipe with large torsion were studied by fluid particle trajectory [17]. Most recently, Cookson et al. [18] quantified the in-plane mixing by using an information entropy measure for helical geometries and varying the radius of helix. It was found that a radius of 0.25D with a pitch of 6D provided the best trade-off between mixing and pressure drop.

Comparatively little has been published on flows in a small-amplitude helically sinuous tube ($r > R$) [4,5,18]. Further, few studies have evaluated what shapes of vascular prostheses could have potential for good patency [4,5,18,19].

Recently, numerical simulations for patient-specific studies are attracting a great amount of attention because of the advantages of providing an inductive method for treating vascular disorders. However, numerical investigations of the influences of hemodynamic parameters are still very important in providing a deductive method for developing innovative vascular prostheses. Thus, the ultimate objective of the present study is to provide an understanding of how the fluid dynamics can be used to control the biological reactivity of blood components interacting with the prosthetic vascular surface or wall, so that further hemodynamic knowledge can be used for physiological and clinical applications to the optimum design of prosthetic grafts, shunts and stent grafts.

2. Methodology

Small-amplitude helically sinuous prosthetic graft models, designed to ensure physiologically relevant swirling flow, were earlier developed and shown to have potential for good patency