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Communication

Wall shear stresses in small and large two-way bypass grafts

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Abstract

Wall shear stress, as one of the most important hemodynamic parameters of the cardiovascular system, has been studied extensively in the numerical and experimental approaches to blood flow in various arteries. In order to clarify the influence of graft diameter on the wall shear stress in a femoral two-way bypass graft, the pulsatile blood flows in two models were simulated with the finite element method. Both models were constructed with different diameters of grafts. The main geometric structure and the boundary conditions were identical for both models. The emphasis was on the comparison analysis of wall shear stresses in the vicinity of the distal anastomosis. The temporal–spatial distributions of wall shear stresses, wall shear stress gradients, and oscillating shear index were analyzed and compared. The present study indicated that femoral artery bypassed with a large graft demonstrated relatively uniform wall shear stresses and small wall shear stress gradients, whereas it does not have advantages in the oscillating shear index. The large model exhibits better and more regular hemodynamic phenomena and may be effective in decreasing the probability of the initiation and development of postoperative intimal hyperplasia and restenosis. Thus, appropriately large grafts are applicable in the clinical practice of femoral two-way bypass operation. More detailed studies are necessary on this problem for the purpose of increasing the success rates of the femoral bypass grafts.

Keywords: Hemodynamics; Numerical simulation; Bypass graft; Anastomosis; Restenosis

1. Introduction

Wall shear stress (WSS), as one of the most important hemodynamic parameter of cardiovascular system, has been studied extensively in the numerical and experimental approaches to blood flow in various arteries. As a critical factor denoting the interaction between the blood flow and the vessel wall, WSS has direct impacts on the morphology and biochemistry of endothelial cells [1–6]. It is agreed that the increasing residence time of atherogenic particles, such as platelets, leukocytes, and macrophages, which could increase the probability of deposition or adhesion of blood particles with the vessel wall, is correlated with hemodynamic WSS. Honda et al. suggest that areas of low WSS are prone to the development of atherosclerotic lesions [1]. Nagel et al. demonstrate the occurrence of spatial wall shear stress gradients (WSSGs) may represent important local modulators of endothelial gene expression at anatomic sites predisposed for atherosclerotic development [3]. White et al. have shown that temporal gradients in shear stress lead to enhanced endothelial proliferation, whereas spatial gradients in shear stress affect endothelial proliferation no differently than steady uniform shear stress [5]. In the cardiovascular circulatory system, pulsatile blood flow produces physiologically oscillatory WSSs with mean values from 0.5 to 4 Pa [7]. However, abnormal WSS conditions may occur at some predilection sites. This irregular WSS may affect vascular biology and arterial wall self-regulation, and may play a significant role in the development of intimal hyperplasia (IH) and thrombus [8–10]. Despite extensive investigation, there are still a number of contentious explanations about the role of hemodynamic WSS in cardiovascular atherosclerosis-related disease.

Femoral bypassing surgery for stenosed arteries is a technical challenge for the surgeon because of the unacceptably

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high rate of postoperative occlusion [11]. The predominant IH and restenosis in the vicinity of distal anastomosis are the clinical causes which are associated with abnormal WSSs at the distal junction area [12]. The hemodynamic WSSs in this region are characterized by dramatic temporal–spatial variation in both magnitude and direction. WSSG has shown its importance in atherogenesis, probably as the local modulator of endothelial gene expression [3,4,9]. Many investigations have demonstrated that low and oscillating WSS, large and sustained temporal–spatial WSSG, etc., are critical hemodynamic mediators for the aggradation of blood cells, the hyperplasia of endothelium cells, the thickening of blood vessel wall and the restenosis of femoral bypassing conduits [5,8,13–16]. Ku et al. studies [13,16] confirmed that low WSS can promote plaques formation and intimal thickening, and marked oscillations in the direction of WSS may enhance atherogenesis. Extremely low WSSs are correlated with cellular proliferation and particle hemodynamics in the bypassing anastomoses [14]. A study by Ojha revealed a strong correlation between sites where IH tends to occur and sites with low WSS at the heel and toe, as well as sites having sharp temporal variations in the magnitude and spatial gradient of the WSS on the arterial floor [15]. However, to date, the role of WSS in the pathogenesis of IH and restenosis of femoral bypass graft remains unclear.

However, it is agreed that geometric configuration of anastomosis has great influences on the hemodynamic WSSs [17,18]. Animal and human studies have shown that arteries adjust their lumen diameter in response to long-term changes in blood flow rate to maintain the normal physiological WSSs [2,10,19]. Clinical observation reveals that a larger graft has more advantages with higher patency rates; therefore, it is reasonable to suspect that graft diameter plays an important role in the hemodynamic WSSs and the development of IH and restenosis [20]. In order to obtain a deeper insight into the relationship between the graft diameter and the hemodynamics, and subsequently, investigate the approaches to the improvement of bypassing surgery with respect to long term patency rates, detailed studies are required. Based on the fact that blood flow from the conventional one-way bypass graft strongly strikes the floor opposite the anastomosis and results in irregular hemodynamics at the anastomosis characterized by disturbed flow patterns and violently changing WSS distributions, we proposed a novel design of anastomosis configuration using symmetrically implanted two-way bypass grafts for the purpose of improving the hemodynamics. The simulation results of unsteady blood flows in the one- and two-way femoral bypass grafts indicated that the flow patterns and WSS distributions in the two-way model are quite different from those in the one-way model [21]. The two-way model features larger longitudinal velocity, less refluence and eddy flow, more uniform WSS distributions and smaller WSSG magnitudes. The hemodynamics in the symmetric two-way bypass grafts are improved and favorable for alleviating the IH and restenosis. For the time being, this novel bypass configuration is not in common clinical practice yet as the sufficient animal experiments are necessary in advance. Even so, the two-way bypass grafts provide an alternative for the bypass surgery with the development of clinical techniques.

In this paper, we will continue our previous research work [21] and analyze the influences of graft diameter on the hemodynamic WSS conditions in the femoral two-way bypass graft. In order to examine, evaluate and characterize the local WSSs in both a small model and a large model with two-way bypass grafts, the physiologically pulsatile blood flows in these models were simulated with the computational fluid dynamics (CFD) method. A great number of studies have approved that numerical analysis of blood flow in arterial segments is of paramount importance in understanding the biomedical pathophysiology of atherosclerosis. CFD analysis is a mature and effective tool for determining the hemodynamic distribution of complex WSS patterns. CFD can easily achieve a high spatial resolution, which is necessary for the calculation of the boundary layer. In this way, not only the calculation precision can be increased significantly, but also the complex WSS and WSSG patterns can be obtained easily. Therefore, via the application of CFD, it is possible to quantitatively analyze the local hemodynamic WSS distributions in regions where atherosclerosis usually occurs.

2. Models and method

2.1. Models

In the present study, the physical models of three-dimensional femoral two-way bypass grafts, with small and large grafts, respectively, have identical geometric configuration (Fig. 1). The host artery, with a fully occluded section,

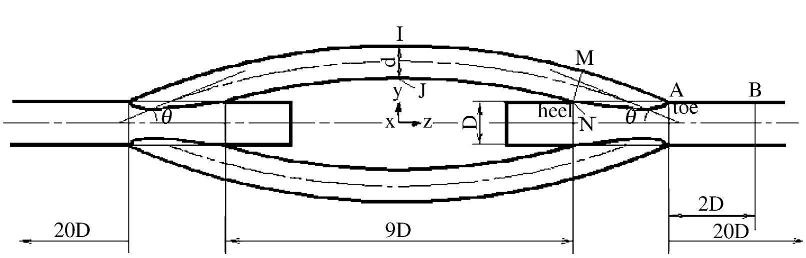

Fig. 1. Geometric model for the calculation.