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Review

Medical application oriented blood flow simulation ☆

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Abstract

In order to show the application of computational fluid dynamics in biomedical engineering, some numerical simulations of blood flow in arteries, such as hemodynamics of bypass graft for stenosed arteries, hemodynamics of stented aneurysm at the aortic arch, hemodynamics of bypass treatment for DeBakey III aortic dissection, and influence of blood flow on the thermal characteristics of microwave ablation, which were performed by the authors, were reviewed. These simulations can be a powerful tool for the computer assisted surgery in medical application.

Keywords: Computer assisted surgery; Hemodynamics; Computational fluid dynamics; Medical application; Cardiovascular system

0. Introduction

The simulation of blood flow is of great importance for understanding the function of the cardiovascular system under normal and abnormal conditions, designing cardiovascular devices, and diagnosing and treating disease. It is helpful and economical that the physician can utilize computational tools to construct and evaluate a combined anatomic/physiologic model to predict the outcome of alternative treatment plans for an individual patient. Computer assisted surgery has become a powerful assistant for the modern medical application.

In the past ten years, we have performed a series of numerical simulations of physiological blood flow in arteries using the computational fluid dynamics (CFD) method in order to investigate the hemodynamic mechanisms in the treatment of some diseases in human tissues and organs.

1. Hemodynamics simulation of bypass graft for stenosed arteries

The bypass graft yields excellent results and remains the modern standard of care for treatment of stenosed arteries in the cardiovascular system. It is convinced that geometry configuration of anastomosis has profound influences on the hemodynamics, such as flow patterns, pressure distribution and wall shear stress (WSS), which are correlated with postoperative occlusion pathogenesis of bypass graft (Honda et al., 2001; Nagel et al., 1999; White et al., 2001). It has been also suggested that high wall shear stress gradient (WSSG) and long residence times might be responsible for the localization of anastomotic intimal hyperplasia (IH) (Lei et al., 1997).

The conventional "1-way" bypass graft inevitably creates disturbed flow at the anastomosis because of its intrinsic asymmetric geometric characteristics. In particular, blood flow from the graft will strongly strike the floor, resulting in flow stagnation and reversed flow. Such flow behavior is unphysiological and can result in non-uniform and violent hemodynamic changes in the bypass graft, and further bring about the possibility of IH and restenosis. In order to improve the hemodynamics induced by the asymmetric geometry of the 1-way bypass graft and increase the

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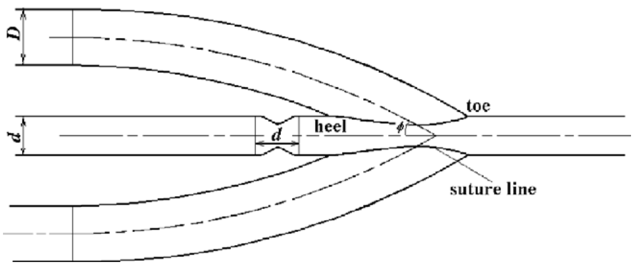

Fig. 1. Geometric model of 2-way bypass graft.

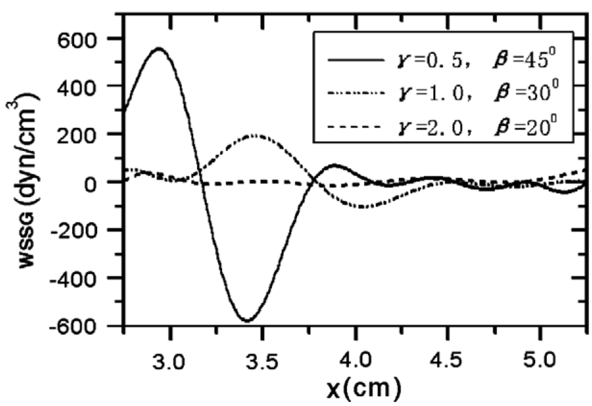

Fig. 2. Comparison of WSSG distribution in optimization cases. γ is the graft-host diameter ratio ($0.5 \leqslant \gamma \leqslant 2.0$), β the junction angle ($20° \leqslant \beta \leqslant 45°$), and X the location along the floor of the distal anastomosis.

treatment effectiveness of bypass graft, we proposed a novel configuration for bypass graft employing a symmetrically implanted 2-way bypass graft (Fig. 1). The temporal and spatial distributions of hemodynamics, such as flow patterns and WSS in the vicinity of the distal anastomoses, were simulated and analyzed (Qiao et al., 2004, 2005b; Qiao and Matsuzawa, 2007). Simulation results showed that the 2-way model possessed favorable hemodynamics with uniform longitudinal flow patterns and WSS distributions, which could decrease the probability of restenosis and improve the effect of the surgical treatment.

Some researchers have studied the relationship between the junction angle and the local hemodynamics of anastomosis (Lei et al., 1997; Perktold et al., 1994). Large junction angles can produce large radial velocities in the cross-section, which increase the secondary flow and decrease the main flow, prolonging the residence times of blood elements in the vicinity of anastomosis and further bringing about restenosis (Cole et al., 2002). Inzoli et al. and Perktold et al. found that a smaller junction angle has more advantages than a larger one (Inzoli et al., 1996; Perktold et al., 1994). We have studied the hemodynamics of 1-way and 2-way femoral bypass grafts with various junction angles ($\varphi = 20°$, $\varphi = 30°$ and $\varphi = 45°$) and graft diameters ($d = 0.4$, 0.6 and 0.8 cm) (Qiao and Liu, 2006a, 2007b; Qiao et al., 2006). The simulation results are coincident with those of Inzoli et al. and Perktold et al.

Large diameter graft can produce relatively large longitudinal velocity, uniform WSS and small WSSG in the host artery, which has positive effects for improving the hemodynamics of bypassing surgery, decreasing the probability of the initiation and development of postoperative IH and restenosis, and increasing the long-term patency rates (Qiao et al., 2007). Based on the hypothesis that non-uniform hemodynamics may trigger abnormal biological processes leading to rapid restenosis and hence early graft failure, Kleinstreuer et al. and Lei et al. were convinced that postoperative disease might be significantly mitigated by finding graft-artery bypass configurations in which the WSSG is approximately zero, thus achieving almost uniform hemodynamics (Lei et al., 1997; Kleinstreuer et al., 1996). They optimized the graft-artery bypass configurations with computer aided design techniques to ameliorate the hemodynamics (Lei et al., 1997). Based on some constructed mathematics models, we have performed the simulation of optimization of CABG hemodynamics. In order to obtain an optimum graft-host diameter ratio and junction angle, the response surface methodology was applied to minimize the WSSG. The comparison of WSSG distribution along the floor of the distal anastomosis in different optimization cases was shown in Fig. 2 (Ma et al., 2007). The result indicated that adopting the graft-host diameter ratio as large as possible and junction angle as small as possible with the help of clinic experiences is advisable in bypass graft surgery.

The "sharp" edges and corners along the suture-line cause stress concentrations and large WSSG. These stress raisers can be eliminated or reduced by employing streamlining the models (Anayiotos et al., 2002).We proposed an end-to-end (ETE) conjunction (Fig. 3) at the distal anastomosis to obtain a streamlined configuration for the bypass graft (Qiao and Matsuzawa, 2004), and performed the numerical simulation. The simulation results indicated that the ETE model is featured with large longitudinal velocity and small secondary flow, and WSSs at the distal anastomosis are uniform and WSSGs are somewhat small. Thus,

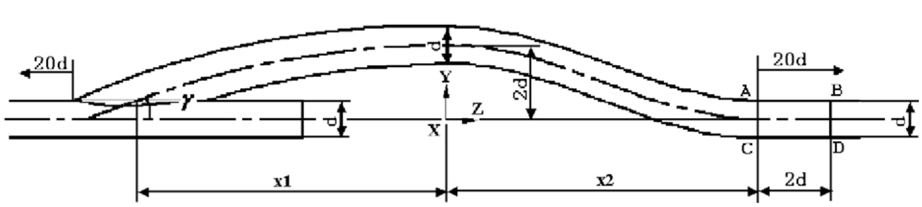

Fig. 3. Geometric model of end-to-end bypass graft.