Available online at www.sciencedirect.com

ScienceDirect

Clinical Biomechanics 23 (2008) S130–S136

CLINICAL BIOMECHANICS

www.elsevier.com/locate/clinbiomech

Review

Medical application oriented blood flow simulation ☆

Aike Qiao *, Youjun Liu

College of Life Science and Bioengineering, Beijing University of Technology, Beijing 100022, China

Received 25 April 2007; accepted 24 September 2007

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

☆ This work was supported by Natural Science Foundation of Beijing (3062003) and National Natural Science Foundation of China (10772010, 30470450).
* Corresponding author.
E-mail addresses: qak@bjut.edu.cn (A. Qiao), lyjlma@bjut.edu.cn (Y. Liu).

0268-0033/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2007.09.018

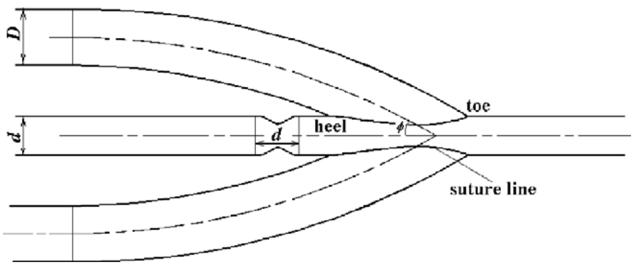

Fig. 1. Geometric model of 2-way bypass graft.

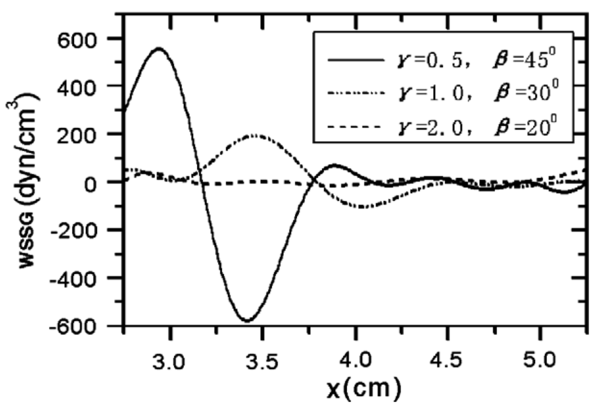

Fig. 2. Comparison of WSSG distribution in optimization cases. γ is the graft-host diameter ratio ($0.5 \leqslant \gamma \leqslant 2.0$), β the junction angle ($20° \leqslant \beta \leqslant 45°$), and X the location along the floor of the distal anastomosis.

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,

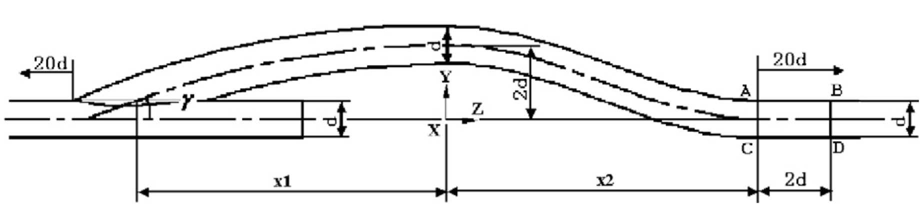

Fig. 3. Geometric model of end-to-end bypass graft.

the ETE anastomosis could consequently improve the flow conditions, decrease the probability of IH and restenosis and might increase the patency rates of bypassing surgery.

Various configurations, such as patched, cuffed, and side-to-side anastomosis are also under consideration in the numerical simulation and clinical application (Cole et al., 2002; Longest et al., 2003; Bonert et al., 2002; Sankaranarayanan et al., 2006). Investigations of improved anastomosis configurations are still ongoing.

2. Hemodynamics simulation of stented aneurysm at the aortic arch

Endovascular stent is commonly used to bridge the aneurysmal orifice since the first trial of Parodi (1995). Despite of the expansive investigation in the endovascular stent for aneurysms, studies of hemodynamics simulation of stented aneurysm at the aortic arch with a localized outpouching (bleb) on top of the dome, at which point aneurysms frequently rupture, are relatively rare. We have studied the hemodynamics in fully stented aortic arch aneurysms harboring a bleb on the dome (Fig. 4a) (Qiao et al., 2005a). The simulation results showed that the intra-aneurysmal flow in the stented aneurysm was significantly attenuated, and the pressure and WSSs were decreased. Flow activity inside the stented aneurysm model is significantly diminished, which agree very well with the studies of Aenis et al. (1997), Lieber et al. (2002) and Liou and Liou (2004). A high pressure zone at the dome of the aneurysm prior to stenting decreases after stent implantation, this phenomena in our simulation also accords with the results of Aenis et al. (1997) and Liou and Liou (2004). The magnitude and pulsatility of the WSSs along the aneurysmal wall were reduced by stenting in our study, specifically in the bleb region. Our results are coincident with those of Shojima et al. (2004). The hemodynamic changes that were observed in our study can help to explain the efficacy of in vivo thrombus formation caused by stenting (Rhee et al., 2002). Considering the widely convinced therapeutic mechanism of endovascular stents, we believe that the stent-induced sluggish flow activity, low pressure, low WSS and hence embolization in the aortic arch aneurysmal sacs can facilitate the occlusion of aneurysms. The hemodynamic characteristics allows us to conclude that we can treat aortic arch aneurysm with bare wire-mesh endovasucular stents.

We found that the stent filaments may cover the orifice of the arterial branches and impede their perfusion. One alternative is to fenestrate the stent filaments at the branches, however it is difficult to correctly position the stent which has sensitive effect on the flow reduction mechanism (Hirabayashi et al., 2003). So we proposed to partly bridge the aneurysmal orifice so as to prevent the branch arteries from being blocked (Fig. 4b). Simulation studies demonstrated that partly stented aneurysm exhibits favorable hemodynamics for thrombus formation (Qiao and Liu, 2006b, 2007a). Flow activity inside the partly stented aneurysm model is significantly diminished. Of course, larger cohort of animal experiments and longer follow-up clinical trials are necessary to confirm our findings and determine the long-term effectiveness of partly bridged endovascular stent therapy.

The shape of the stent (e.g., helix-versus mesh-shaped stents) (Liou et al., 2004), the size of the orifice, the porosity of a stent (Rhee et al., 2002) and the stent filament size (Lieber et al., 2002; Bando and Berger, 2003) are important factors that influence the treatment effectiveness of stented aneurysms. The hemodynamics simulations concerning the optimization of all these factors are still open to question. Other prospective approaches, such as stent-graft (Chuter et al., 2003) (covered stent, coated by porous polyurethane) (Ruiz et al., 1995), coiling (Asakura et al., 2003), and multiple overlapping stents (Doerfler et al., 2004), are emerging as therapeutic alternatives to surgery for the treatment of aneurysms, and are under way for clinical trial.

With regard to the fact that covered stent grafts may block flow into aortic side branches and result in degeneration and restenosis of the parent vessel, we propose locally patched and/or fenestrated stent-graft for the treatment of aortic aneurysms with side branches. This tentative plan is still under studies in our research work.

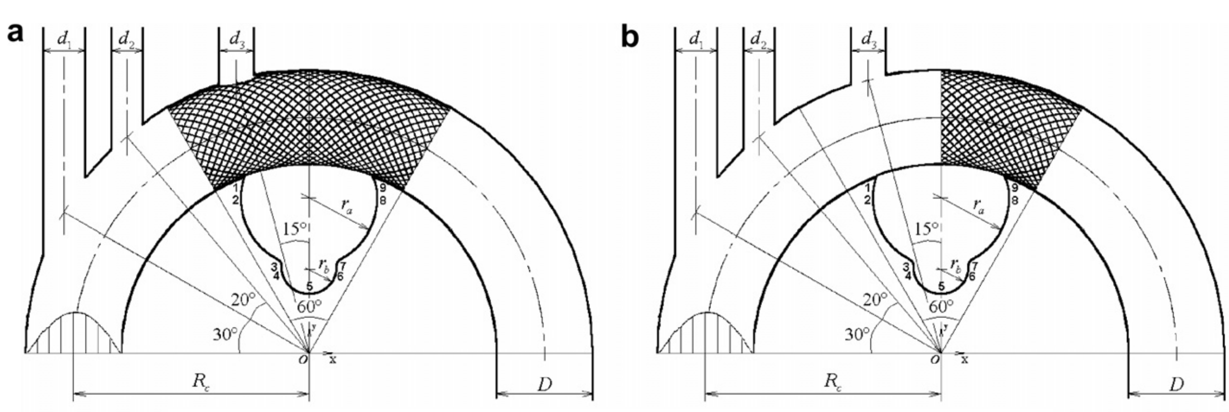

Fig. 4. Geometric models of the stented aortic arch aneurysm harboring a bleb on its dome. (a) Fully stented. (b) Partly stented.

3. Hemodynamics simulation of bypass treatment for DeBakey III aortic dissection

Aortic dissection is one of the usually happened fateful diseases among the aortic pathological changes. Hemodynamics also play an important role in this dissecting disease. Angouras et al. analyzed the influence of blood flow on the aortic wall stresses and the aortic dissection by performing animal experiments (Angouras et al., 2000). Chang et al. measured the blood flow patterns in the true and false lumens of dissection using magnetic resonance device (Chang et al., 1991). Giannakoulas et al. analyzed the wall stress and deformation under different blood pressures using finite element method (Giannakoulas et al., 2005). Zannoli et al. experimentally studied the mechanical factors influencing the treatment of aortic dissection (Zannoli et al., 2006). Although many literatures reported various studies on aortic dissection, few are related with clinical surgery mechanisms of aortic dissection. Different therapeutic treatment should be employed to different aortic dissection type. In 1979, Carpentier developed for the first time the thromboexclusion approach to treat DeBakey III aortic dissection (Carpentier et al., 1981). Clinical trails found that bypass graft alone can also achieve great effects in this surgery. However, this surgical therapy is not widely popularized because the fundamental mechanisms in it have not been well understood yet. To the best of our knowledge, up to now no one has ever studied by means of numerical simulation the hemodynamics of bypass graft treatment for aortic dissection.

We numerically simulated the hemodynamics of bypass graft treatment for DeBakey III aortic dissection using CFD method to assess the hemodynamics feasibility of this therapy (Qiao, 2007). The result illustrated that the pressure and blood flow activities in the false lumen decreased after the bypass graft operation (Fig. 5), which is profitable for alleviating the propagation of aortic dissection and promoting the thromboexclusion of dissecting sac. Bypass graft can be feasible alternative, and this procedure can provide valuable surgical planning for the clinical application.

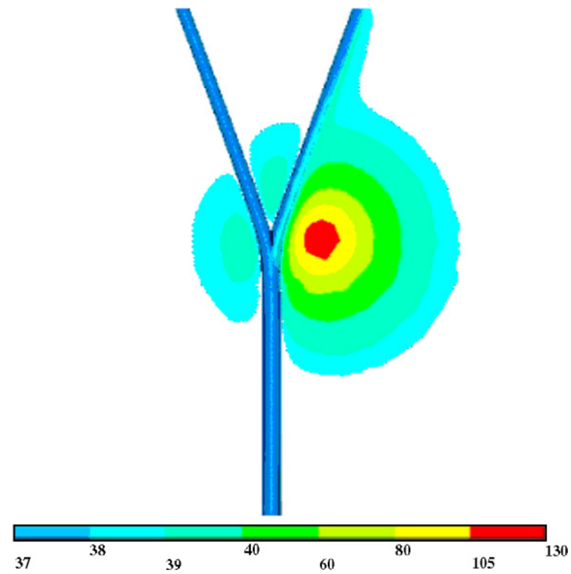

Fig. 6. Simulation of temperature distribution in the vicinity of arterial bifurcation.

The bypass graft treatment for DeBakey III aortic dissection attributes outstanding advantages compared with conventional endovascular stent-grafting procedures in such aspects as short operation time, low cost, little inva-

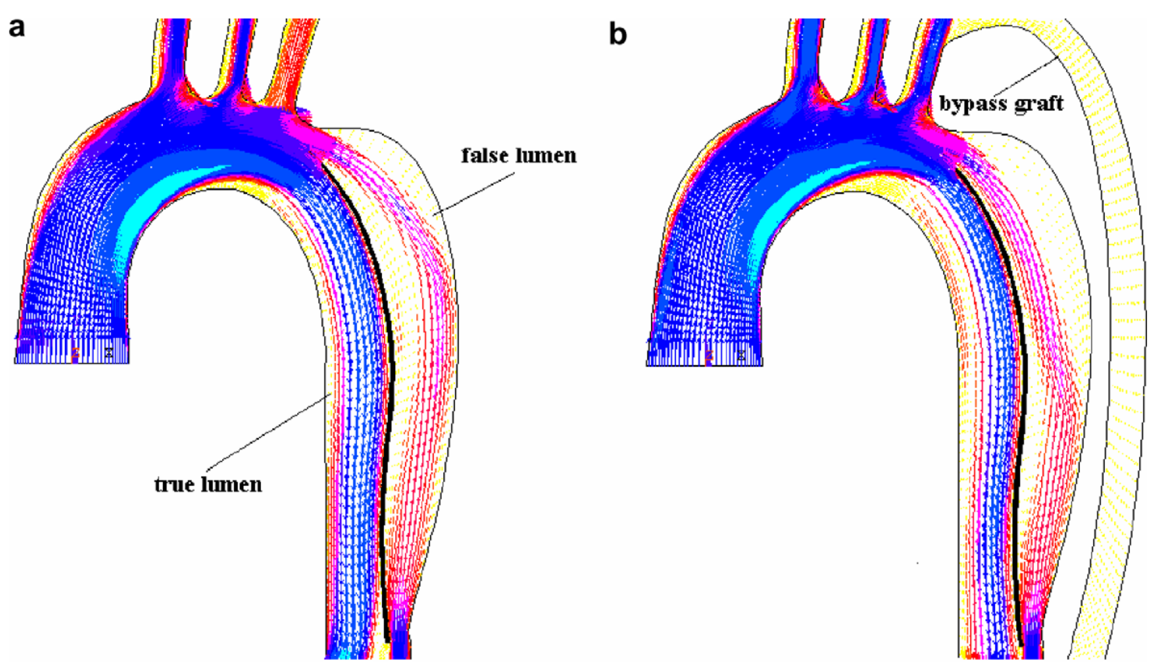

Fig. 5. Flow patterns in the non-bypassed and bypassed models. (a) Non-bypassed model. (b) Bypassed model.

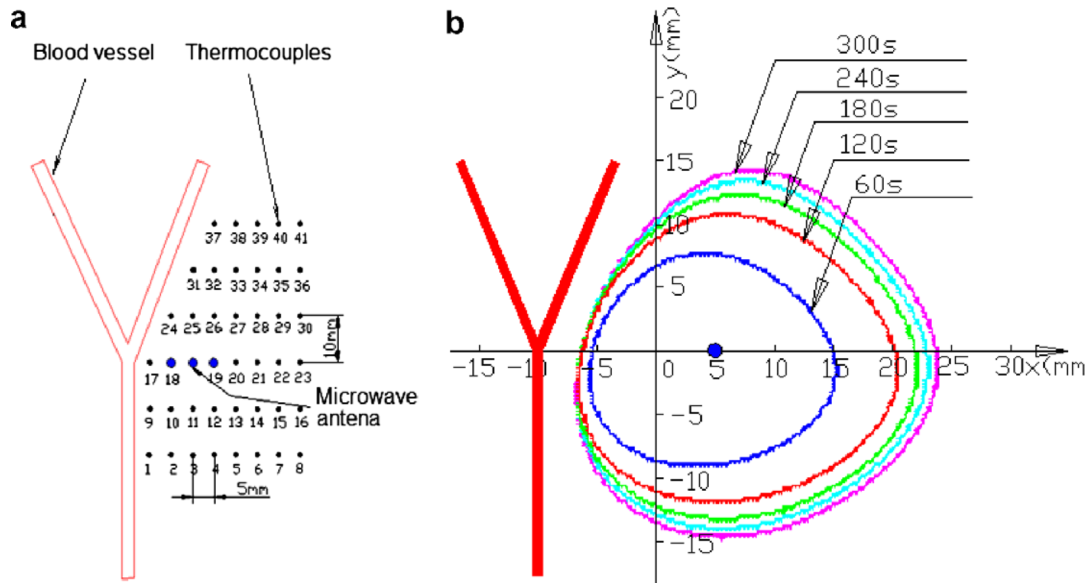

Fig. 7. Positions of antenna and temperature contours at different times.

sion and simplicity of operation, etc. (Qiao et al., 2007). This therapy can be widely extended to medium and small hospitals. Thus, it is a promising clinical procedure for the treatment of DeBakey III aortic dissection. However, continuous close follow-up examination is mandatory and long-term results have to be awaited to evaluate the actual effectiveness of this therapy.

4. Influence of blood flow on the thermal characteristics of microwave ablation

A major problem in the quality assurance of thermal ablations is temperature distribution control, in which the impact of blood flow, especially flow in large arterial vessels, has to be accounted for because cold blood enters the locally heated volume, applies cooling, removes heat and by doing so can severely affect the temperature distribution (Lagendijk, 1982).

The temperature distribution in liver-like material heated by microwaves was simulated using the finite element method in order to reveal the detailed thermal characteristics of microwave ablation in the vicinity of an arterial bifurcation (Fig. 6) (Liu et al., 2006). Coupled fluid flow and solid heat transfer were taken into consideration, and the analysis was three-dimensional. It was found that interaction between the recirculation flow in the bifurcation and the heat transfer in the surrounding tissue makes the temperature distribution near the bifurcation complicated. Most importantly, after a period of continuous heating with constant microwave output power, the maximum temperatures caused by the ablation do not always increase with the distance between the antenna and the bifurcation. It can be concluded that inadequate ablations can be the result of not only a close proximity between the antenna and the blood vessel, but also a complicated blood flow in large vessels whose structure causes recirculation flow.

We have also performed some experimental studies. Microwave ablation therapy using a water-cooled antenna was studied experimentally in a muscle-equivalent phantom. The development of the heating pattern induced by the microwave antenna was determined from the thermocouple-measured temperature field, and the influence of the cooling water flow within the antenna on temperature distribution and heating pattern was investigated. The results showed that the shape of the heating pattern was pear-like, and the enlarging rate of the heating pattern decreased with heating time (Liu et al., 2007). The influences of flow rate in an arterial bifurcation and the distance between the vessel and the microwave antenna on the temperature distribution were experimentally studied (Fig. 7) (Li et al., submitted for publication). The higher was the blood velocity, the smaller was the heating pattern. There was a recirculation zone in the daughter branching vessel immediately after the bifurcation which actually acted as a thermal insulating layer between the tissue and the blood. The results of experiment and numerical simulation attribute satisfactory qualitative consistency.

Studying the bio-heat transformation near an arterial bifurcation can provide a basis for understanding the impact of complicated vasculature on thermal ablation, and a helpful guidance for clinical operation.

5. Summary

CFD has been convinced as a valuable approach to the numerical simulation study of blood flow in arteries because of its capability of obtaining quantitative hemodynamics parameters. The individual variability and inherent complexity of human biological systems is such that idealized modeling, diagnostic imaging and empirical data alone are insufficient to predict the outcome of a given treatment for an individual patient. With the development of modern angiographic techniques, such as magnetic resonance imaging, it is now possible to quantify blood flow in anatomically and physiologically real patient-specific models, which enables an entirely new application of biomechanics, namely predicting changes in blood flow resulting from possible therapeutic interventions for individual patients (Taylor et al., 1999). Medical application oriented blood flow simulation enables physicians, medical device manufacturers, and pharmaceutical and biotechnology manufacturers to get insight into pre- and post-operation. Many more applications of blood flow simulation will undoubtedly be conceived and will shape our research field in the years to come (Steinman and Taylor, 2005).

References

Aenis, M., Stancampiano, A.P., Wakhloo, A.K., Lieber, B.B., 1997. Modeling of flow in a straight stented and nonstented side wall aneurysm model. J. Biomech. Eng. 119, 206–212.

Anayiotos, A.S., Pedroso, P.D., Eleftheriou, E.C., Venugopalan, R., Holman, W.L., 2002. Effect of a flow-streamlining implant at the distal anastomosis of a coronary artery bypass graft. Ann. Biomed. Eng. 30, 917–926.

Angouras, D., Sokolis, D.P., Dosios, T., Kostomitsopoulos, N., Boudoulas, Harisios, Skalkeas, G., Karayannacos, P.E., 2000. Effect of impaired vasa vasorum flow on the structure and mechanics of the thoracic aorta: implications for the pathogenesis of aortic dissection. Eur. J. Cardio-thorac. Surg. 17, 468–473.

Asakura, F., Tenjin, H., Sugawa, N., Kimura, S., Oki, F., 2003. Evaluation of intra-aneurysmal blood flow by digital subtraction angiography: Blood flow change after coil embolization. Surg. Neurol. 59, 309–318.

Bando, K., Berger, S.A., 2003. Research on fluid-dynamic design criterion of stent used for treatment of aneurysms by means of computational simulation. Comput. Fluid Dyn. J. 11, 527–531.

Bonert, M., Myers, J.G., Fremes, S., Williams, J., Ethier, C.R., 2002. A numerical study of blood flow in coronary artery bypass graft side-to-side anastomosis. Ann. Biomed. Eng. 30, 599–611.

Carpentier, A., Deloche, A., Fabiani, J.N., Chauvaud, S., Relland, J., Nottin, R., Vouhe, P., Massoud, H., Dubost, C., 1981. New surgical approach to aortic dissection flow reversal and thromboexclusion. J. Thorac. Cardiovasc. Surg. 81, 695–698.

Chang, J., Friese, K., Caputo, G.R., Kondo, C., Higgins, C.B., 1991. MR measurement of blood flow in the true and false channel in chronic aortic dissection. J. Comput. Assist. Tomogr. 15, 418–423.

Chuter, T.A.M., Schneider, D.B., Reilly, L.M., Lobo, E.P., Messina, L.M., 2003. Modular branched stent graft for endovascular repair of aortic arch aneurysm and dissection. J. Vasc. Surg. 7, 859–863.

Cole, J.S., Watterson, J.K., O'Reilly, M.J.G., 2002. Numerical investigation of the hemodynamics at a patched arterial bypass anastomosis. Med. Eng. Phys. 24, 393–401.

Doerfler, A., Wanke, I., Egelhof, T., Stolke, D., Forsting, M., 2004. Double-stent method: therapeutic alternative for small wide-necked aneurysms. Technical note. J. Neurosurg. 100, 150–154.

Giannakoulas, G., Giannoglou, G., Soulis, J., Farmakis, T., Papadopoulou, S., Parcharidis, G., Louridas, G., 2005. A computational model to predict aortic wall stresses in patients with systolic arterial hypertension. Med. Hypotheses 65, 1191–1195.

Hirabayashi, M., Ohta, M., Rüfenacht, D.A., Chopard, B., 2003. Characterization of flow reduction properties in an aneurysm due to a stent. Phys. Rev. 68, 1–6.

Honda, H.M., Hsiai, T., Wortham, C.M., Chen, M., Lin, H., Navab, M., Demer, L.L., 2001. A complex flow pattern of low shear stress and flow reversal promotes monocyte binding to endothelial cells. Atherosclerosis 158, 385–390.

Inzoli, F., Migliavacca, F., Pennati, G., 1996. Numerical analysis of steady flow in aorto-coronary bypass 3D model. J. Biomech. Eng. 118, 172–179.

Kleinstreuer, C., Lei, M., Archie Jr., J.P., 1996. Geometric design improvements for femoral graft-artery junctions mitigating restenosis. J. Biomech. 29, 1605–1614.

Lagendijk, J.J.W., 1982. The influence of blood flow in large vessels on the temperature distribution in hyperthermia. Phys. Med. Biol. 27, 17–23.

Lei, M., Kleinstreuer, H.C., Archie, J.P., 1997. Hemodytnamics simulations and computer-aided designs of graft-artery junctions. J. Biomech. Eng. 119, 343–348.

Li, L., Nan, Q., Yang, X., Liu, Y., Qiao, A. Experimental study on thermal field in vicinity of bifurcation vessel in microwave ablation therapy. Int. J. Hyperther., submitted for publication.

Lieber, B.B., Livescu, V., Hopkins, L.N., Wakhloo, A.K., 2002. Particle image velocimetry assessment of stent design influence on intra-aneurysmal flow. Ann. Biomed. Eng. 30, 768–777.

Liou, T.M., Liou, S.N., 2004. Pulsatile flows in a lateral aneurysm anchored on a stented and curved parent vessel. Exp. Mech. 44, 253–260.

Liou, T.M., Liou, S.N., Chu, K.L., 2004. Intra-aneurysmal flow with helix and mesh stent placement across side-wall aneurysm pore of a straight parent vessel. J. Biomech. Eng. 126, 36–43.

Liu, Y.J., Qiao, A.K., Nan, Q., Yang, X.Y., 2006. Thermal characteristics of microwave ablation in the vicinity of an arterial bifurcation. Int. J. Hyperther. 22, 491–506.

Liu, Y.J., Yang, X.Y., Nan, Q., Xiao, J.Y., Li, L., 2007. Phantom experimental study on microwave ablation with water-cooled antenna. Int. J. Hyperther. 23, 281–386.

Longest, P.W., Kleinstreuer, C., Archie Jr., J.P., 2003. Particle hemodynamics analysis of Miller cuff arterial anastomosis. J. Vasc. Surg. 38, 1353–1362.

Ma, B., Sui, Y., Qiao, A., 2007. Optimization and analysis of graft-host diameter ratio and junction angle in coronary artery bypass graft. J. Med. Biomech. 22, 247–250.

Nagel, T., Resnick, N., Dewey Jr., C.F., Gimbrone Jr., M.A., 1999. Vascular endothelial cells respond to spatial gradients in fluid shear stress by enhanced activation of transcription factors. Arterioscler. Thromb. Vasc. Biol. 19, 1825–1834.

Parodi, J.C., 1995. Endovascular repair of abdominal aortic aneurysms and other arterial lesions. J. Vasc. Surg. 21, 549–557.

Perktold, K., Tatzl, H., Rappitsch, G., 1994. Flow dynamic effect of the anastomotic angle: a numerical study of pulsatile flow in vascular graft anastomoses models. Technol. Health Care 1, 197–207.

Qiao, A., 2007. Hemodynamics simulation of bypass treatment for DeBakey III aortic dissection. In: The Third B-J-K Symposium on Biomechanics. Kanazawa, Japan, March.

Qiao, A., Liu, Y., 2006a. Influence of graft-host diameter ratio on the hemodynamics of CABG. Bio-Med. Mater. Eng. 16, 189–201.

Qiao, A., Liu, Y., 2006b. Hemodynamics simulation of aortic arch aneurysm with partly bridged endovascular stent. World Congress on Medical Physics and Biomedical Engineering. Seoul, Korea, August 2006.

Qiao, A., Liu, Y., 2007a. Simulation of treatment for aortic arch aneurysms with half implanted stent. J. Beijing Univ. Technol. 33, 423–427.

Qiao, A., Liu, Y., 2007b. Numerical study of hemodynamics comparison between small and large femoral bypass grafts. Communications in Numerical Methods in Engineering. Published Online in Wiley InterScience (www.interscience.wiley.com), doi: 10.1002/cnm.1012, 15 May 2007.

Qiao, A., Matsuzawa, T., 2004. Hemodynamics of end-to-end femoral bypass graft. ASME/JSME Pressure Vessels and Piping Conference. Computational Technologies for Fluid/Thermal/Chemical Systems with Industrial Applications. San Diego, USA. PVP. 491–2, pp. 103–112, July 25–29.

Qiao, A., Matsuzawa, T., 2007. Haemodynamic simulation in a novel design for femoral bypass grafts. Biorheology 44, 103–124.

Qiao, A., Zeng, Y., Xu, X., 2004. Numerical simulations of stenosed femoral artery with symmetric 2-way bypass graft. Bio-Med. Mater. Eng. 14, 167–174.

Qiao, A., Liu, Y., Chang, Y., Matsuzawa T., 2005a. Computational study of stented aortic arch aneurysms. In: 27th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. Shanghai, China, September 2005.

Qiao, A., Liu, Y., Li, S., Zhao, H., 2005b. Numerical simulation of physiological blood flow in 2-way coronary artery bypass grafts. J. Biol. Phys. 31, 161–182.

Qiao, A., Liu, Y., Guo, Z., 2006. Wall shear stresses in small and large 2-way bypass grafts. Med. Eng. Phys. 28, 251–258.

Qiao, A., Li, X., Zhang, H., 2007. Mechanism of the initiation, propagation and treatment of aortic dissection. J. Beijing Univ. Technol. 33, 959–963.

Rhee, K., Han, M.H., Cha, S.H., 2002. Changes of flow characteristics by stenting in aneurysm models: influence of aneurysm geometry and stent porosity. Ann. Biomed. Eng. 30, 894–904.

Ruiz, C.E., Zhang, H.P., Douglas, J.T., Zuppan, C.W., Kean, C.J., 1995. A novel method for treatment of abdominal aortic aneurysms using percutaneous implantation of a newly designed endovascular device. Circulation 91, 2470–2477.

Sankaranarayanan, M., Ghista, D.N., Poh, C.L., Seng, T.Y., Kassab, G.S., 2006. Analysis of blood flow in an out-of-plane CABG model. Am. J. Physiol. Heart Circ. Physiol. 291, 283–295.

Shojima, M., Oshima, M., Takagi, K., Torii, R., Hayakawa, M., Katada, K., Morita, A., Kirino, T., 2004. Magnitude and role of wall shear stress on cerebral aneurysm computational fluid dynamic study of 20 middle cerebral artery aneurysms. Stroke 35, 2500–2505.

Steinman, D.A., Taylor, C.A., 2005. Flow imaging and computing: large artery hemodynamics. Ann. Biomed. Eng. 33, 1704–1709.

Taylor, C.A., Draney, M.T., Ku, J.P., Parker, D., Steele, B.N., Wang, K., Zarins, C.K., 1999. Predictive medicine: computational techniques in therapeutic decision-making. Comput. Aided Surg. 4, 231–247.

White, C.R., Haidekker, M., Bao, X., Frangos, J.A., 2001. Temporal gradients in shear, but not spatial gradients, stimulate endothelial cell proliferation. Circulation 103, 2508–2513.

Zannoli, R., Corazza, I., Branzi, A., 2006. Simulation of a mechanical approach to treat aortic dissection. In: Proceeding of the 5th World Congress of Biomechanics, Germany, July 29th – August 4th, 2006. Journal of Biomechanics, 39 (Suppl. 1), s309.