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Hemodynamics of the string phenomenon in the internal thoracic artery grafted to the left anterior descending artery with moderate stenosis

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ABSTRACT

Purpose: The internal thoracic artery is the choice of graft for coronary artery bypass grafting due to the excellent long-term patency. However internal thoracic artery graft failures still occur due to diffuse narrowing, known as the string phenomenon. Studies suggest that the string phenomenon is caused by competitive flow when the coronary stenosis is not serious, but the hemodynamics of the string phenomenon are still unclear. The purpose of this study is to clarify the hemodynamic characteristics of the string phenomenon.
Materials: A patient-specific 3-dimensional model of the aortic arch and coronary arteries was reconstructed. A moderate stenosis was applied to the left anterior descending artery. The internal thoracic artery was used to bypass the stenosis. Two further 3D models were built to study the hemodynamics of the string phenomenon.
Methods: A numerical study was performed by coupling the 3D artery model with 0-dimensional lumped parameter model of the cardiovascular system.
Results: The graft flow, native coronary flow, wall shear stress and oscillatory shear index were calculated and illustrated. Inverse flow and high oscillatory shear index appeared on the internal thoracic artery graft when the stenosis was moderate.
Conclusion: High oscillatory shear index might be the major hemodynamic characteristic of the string phenomenon in internal thoracic artery graft. The inverse graft flow and the difference in graft flow caused by clamping the stenosis can be used to evaluate the probability of observing the string phenomenon.

1. Background

The internal thoracic artery (ITA) is the choice of graft for coronary artery bypass grafting due to the excellent long-term patency of left ITA when grafted to the left anterior descending coronary artery. The 5, 10 and 15 year patencies of ITA graft have been reported as 98%, 95% and 88% respectively (Tatoulis et al., 2004). However, many reports of ITA graft failure exist due to the so-called string phenomenon. The string phenomenon, or string sign, was first reported by Barner (1974). Seki et al. (1992) described it as the long-term postoperative luminal narrowing resulting in the diameter less than 1 mm, while Nakajima et al. (2004) defined it as suffused stenosis in the arterial graft with a stenosis degree of more than 50%. Thus the string phenomenon in ITA is an intermediate process between shrinking and loss of function or occlusion (Kitamura et al., 1992).

Most researchers hold the view that the string phenomenon is caused by the competitive flow when the stenosis in the native coronary artery is not serious (Geha and Baue, 1979; Hashimoto et al., 1996; Kolozsvari et al., 2012; Manabe et al., 2010; Siebenmann et al., 1993). According to Berger et al. (2004) the degree of stenosis is the most important factor affecting the incidence of ITA graft occlusion; the incidence of ITA graft occlusion is up to 79%, when the native coronary stenosis degree is less than 50%. A study by Shimizu et al. (2004) indicated that the string phenomenon appeared in all patients with moderate or mild stenosis (stenosis degree $<42\%$) at four weeks after surgery, and after one year, all ITA

Abbreviations: ITA, Internal thoracic artery; 3D, 3-dimensional; 0D, 0-dimensional; LAD, Left anterior descending artery; LPM, Lumped parameter model; WSS, Wall shear stress; OSI, Oscillatory shear index; CABG, Coronary artery bypass grafting; CFD, Computational fluid dynamics; CT, Computed tomography; SVG, Saphenous vein graft

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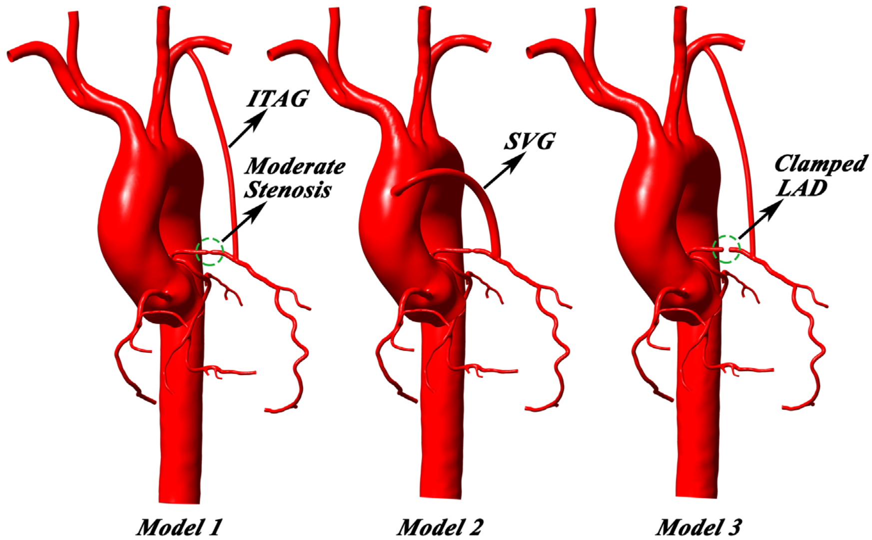

Fig. 1. The reconstructed 3D models. In Model 1, ITAG was used to bypass a moderate stenosis; in Model 2, SVG was used to bypass the same stenosis; in Model 3, ITAG was used to bypass a clamped LAD.

grafts were occluded when stenosis degree was less than 33%. Moreover, it was reported that 4/5 of the ITA grafts applied on patients with moderate stenosis (stenosis degree $<$ 50%) were occluded one or two years after surgery (Seki et al., 1992). Siebenmann et al. (1993) reported that the branch of a Y-type ITA graft used to bypass the moderate stenosis (stenosis degree $<$ 50%) became occluded, while the branch used to bypass the serious stenosis (stenosis degree $>$ 70%) was still patent in the same patient.

Many researchers have focused on the relationship between the stenosis rate and the string phenomenon of ITA grafts since the surgical results may be affected by the adaptive response to hemodynamic factors (Butany et al., 1998; Leask et al., 2005). However few researchers have studied the hemodynamic details of the string phenomenon in ITA grafts. Interestingly, while saphenous vein graft (SVG) thrombosis is the major cause of morbidity and mortality following surgery (Motwani and Topol, 1998; Peykar et al., 2004), some studies have indicated that the native coronary stenosis degree does not affect the patency of SVG (Desai et al., 2004; Urschel et al., 1990). This may suggest that the hemodynamics of SVG and ITA grafts differ, but any differences are not clearly understood.

Usually, CABG was only applied on patients with stenosis in LAD, LCX and RCA at the same time. But if the degree of stenosis in one of the three branches is moderate, the surgeon will face a big problem – Whether the moderate stenosis should be bypassed or not? This problem is frequently exists in clinical. In this study, in order to simplify the study and highlight the purpose of this study, only the moderate stenosis in LAD was taken into consideration.

The 0D/3D coupling method was used in this study to perform a numerical simulation by coupling the lumped parameter model (LPM; 0D sub-model) and 3D vascular sub-models. This is an advanced method which has already been used in some related hemodynamic research (Sankaran et al., 2012; Taylor et al., 2013). The interaction between two different dimensional sub-models in a numerical simulation reproduces relatively more realistic conditions than a classical computational fluid dynamics (CFD) simulation, and it is possible to simulate the hemodynamics of both the 3D artery and the 0D cardiovascular system within one frame at the same time.

This work studies the hemodynamics of the string phenomenon by comparing the hemodynamics of an ITA in a high level of competitive flow (left anterior descending artery (LAD) stenosis degree $\approx$ 50%), with both the ITA at zero competitive flow (LAD occluded) and an SVG in a high level of competitive flow. The purpose was to elucidate the hemodynamic characteristics of the string phenomenon in ITA grafts.

2. Materials and methods

2.1. Three-dimensional reconstruction and computational models

Patient data from a 55-year-old male were provided by Anzhen Hospital. The patient's personal information was anonymized prior to analysis of the data. The cardiac output of the patient was measured to be 4.6 L/min by Doppler ultrasound. Computed tomography (CT) imaging using 460 slices, each of 512 $\times$ 512 pixels, was used for 3D reconstruction. The distance between each adjacent slice was 1 mm. The 3D anatomic geometry was reconstructed by using Mimics^{TM} through both threshold segmentation and manual segmentation. Gaussian filtering was adopted to smooth the reconstructed surface. A moderate stenosis (stenosis degree $\approx$ 50%) was applied to the LAD by using 'PHANTOM DESKTOP' (a kind of force feedback device) and 'Freeform' (software of the 3D modeling system), both developed by Geomagic^{TM}. Virtual surgery comprising either an ITA graft (Model 1) or SVG (Model 2) were implemented on the 3D model with moderate stenosis. The diameter of the ITA and the diameter of the SVG were 3 mm and 5 mm, respectively. In order to compare the hemodynamics of the ITA graft in a high and a low degree of competitive flow, a third 3D model (Model 3) with an ITA graft, in which the LAD was blocked entirely. The three 3D models are illustrated in Fig. 1.

The 3D sub-models were meshed to generate the computational models. A hexahedral mesh was generated mainly by using the size control method with the assistance of the commercial software ANSYS-CFX (ANSYS^{TM}). The mesh was refined in the areas of interest to make the simulation results more precise as the resolution was improved. The node and element numbers for the models are listed in Table 1.

The number of nodes and elements in the three models are within the same order of magnitude. A steady state grid sensitivity analysis was carried out to ensure that the numbers of nodes and elements are large enough to ensure that the simulation results were stable and credible. During the grid sensitivity analysis, both the inlet pressure and area-averaged wall shear stress (WSS) were measured. The difference of inlet pressure and WSS are all within 0.5% for the last mesh that used in this study, as listed in Table 2. Finally, based on these mesh, it cost about 30 h for each case of simulation.

In the 3D simulation, it was assumed that the vessel walls were rigid. The blood flow was treated as an incompressible viscous Newtonian fluid. The density of the blood flow was 1050 kg/m^3 and the dynamic viscosity was 0.0035 Pa s.

2.2. The 0D/3D coupled model

The lumped parameter models (LPM/0D part) used in this study were as described by Taylor et al. (2013). On the basis of both the 3D vascular models and the LPMs, 0D/3D coupled models were constructed, as illustrated in Fig. 2 for Model 1. The boundary conditions of the 3D part were supplied by the 0D calculation and