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Hemodynamic Based Surgical Decision on Sequential Graft and Y-Type Graft in Coronary Artery Bypass Grafting

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Abstract: **Purpose:** Sequential graft and Y-type graft are two different surgical procedures in coronary artery bypass grafting (CABG). The hemodynamic environment of them are different, that may cause different short-term surgical result and long-term patency. In this study, the short-term and long-term result of sequential and Y-type graft was discussed by comparing the hemodynamics of them.
Materials and Methods: Two postoperative 3-dimensional (3D) models were built by applying different graft on a patient-specific 3D model with serious stenosis. Then zero-dimensional (0D)/3D coupled simulation was carried out by coupling the postoperative 3D models with a 0D lumped parameter model of the cardiovascular system.
Results: The flow rate of native coronary arteries and grafts are all calculated and illustrated in this paper. No significant difference of the native coronary arteries flow and graft flow exists between two surgical procedures. The wall shear stress (WSS) and streamline were also depicted. The graft WSS of sequential graft is 19.1% higher than Y-type graft. While flow separation appears at the bifurcation of Y-type graft.
Conclusion: The short-term outcomes of sequential graft and Y-type graft are almost the same. But it can be found from the hemodynamics factors that the long-term patency of the sequential graft is better.

Keywords: 0D/3D coupling Simulation, Hemodynamics, Coronary Artery Bypass Grafting (CABG), Computational Fluid Dynamics (CFD).

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1 Introduction

Coronary artery disease (CAD) is within the group of cardiovascular diseases of which it is the most common type [1-3]. Coronary artery bypass grafting (CABG) is a surgery in clinical to relieve angina and reduce the risk of death caused by coronary artery disease. Autologous arteries or veins are grafted to the coronary arteries to bypass stenosis and improve the blood supply to the myocardium [4]. In 2013 CAD was the most common cause of death globally, resulting in 8.14 million deaths (16.8%) up from 5.74 million deaths (12%) in 1990 [1]. In 2011, the volume of CABG was about 213700 procedures in United States [5]. Saphenous vein graft (SVG) was still used in the majority of CABG procedures [6]. In spite the fact that SVG failure is the major cause of morbidity and mortality [7, 8]. Some studies show that the adaptive response to hemodynamic factors, i.e. wall shear stress (WSS) may lead to SVG failure [9, 10]. While, hemodynamic factors are sensitive to the geometry, different surgical procedures will lead to different hemodynamic environment [11, 12]. The sequential graft and Y-Type graft have been used frequently in clinical [13, 14]. Moreover, some clinical studies have also discussed the long-term results of them [15, 16]. But the hemodynamic reasons of the long-term results have not been studied before.

In this study, the short-term and long-term surgical results of sequential graft and Y-Type graft were studied by comparing the hemodynamic environments of them, to find out the hemodynamic reason of the difference on the short-term and/or long-term results. SVG was used in these two surgical procedures. Both of them were applied on a patientspecific 3D model with stenosis in the left main coronary artery (LM), the proximal left anterior descending artery (LAD) and the proximal left circumflex artery (LCX).

In our previous study, the hemodynamic effect of Y-type graft was discussed by comparing it with normal graft [17]. Results suggested that the long-term patency of normal graft is better. But the Y-type graft only have one anastomosis on the aorta, which is better than the normal graft especially for the patient with serious arteriosclerosis aorta. So it is meaningful to study on the difference of hemodynamic between the sequential graft and Y-type graft, as both of them only have one anastomosis on the aorta.

In summary, the purpose of this study is to evaluate the short-term and long-term surgical results of the sequential graft and Y-type graft, by comparing the hemodynamic environments of them. Furthermore, the graft type with better performance may be found out.

2 Materials and Method

2.1 Patient-specific 3D Model

The patient-specific 3D model used in this paper was based on the patient data which has been published in our previous study [17]. The data is retrieved from a 65 years old male patient with CAD provided by Beijing Anzhen Hospital. The patient's personal information was anonymized and de-identified prior to analysis. The 3D model was reconstructed based on CT images through both the threshold segmentation and manual segmentation. The reconstructed surface the 3D model was smoothen by applying Gaussian filtering.

2.2 Postoperative Model with Different Graft

The virtual surgery of the two different graft were implemented based on "PHANTOM DESKTOP" (a kind of force feedback device) and "Freeform" (a software of 3D modeling system), both of them were developed by Geomagic^{TM}. The diameter of the SVG was 3.5 mm for these two surgical procedures. Thus, two postoperative model with sequential graft (Model 1) and Y-type graft (Model 2) were built, as demonstrated in Fig.1.

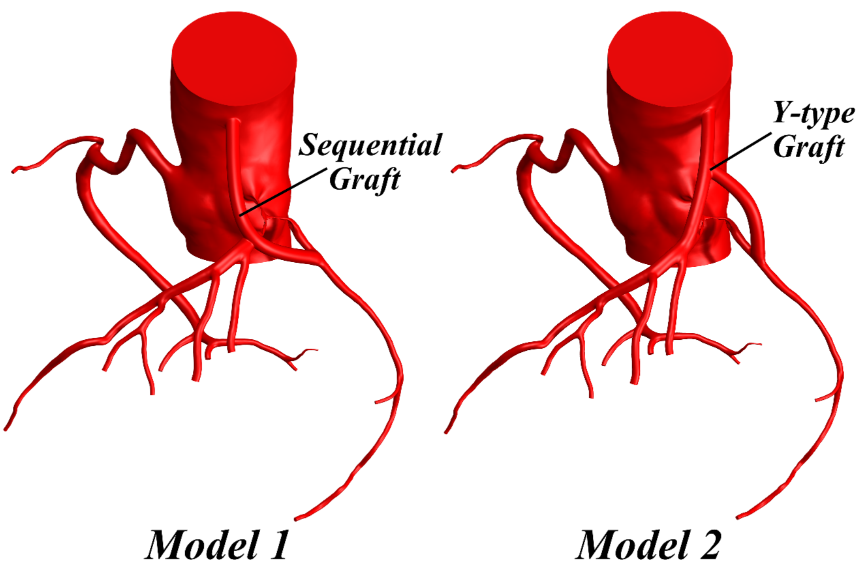

Figure 1: The two 3D models with different graft in CABG.

The postoperative models are meshed to generate the computational models. Hexahedral mesh is generated based on the commercial software ANSYS-CFX (ANSYS^{TM}).

The resolution of the mesh in the areas of interest is improved to make the simulation results precise. In order to make the simulation results stable and credible, a steady state grid sensitivity analysis was carried out to ensure that the numbers of nodes and elements are large enough. The nodes and elements number are listed in Table 1.

Table 1: The nodes and elements numbers of the 3D models.

Model	Nodes	Elements
1	935987	1297654
2	926234	1259562

In the 3D calculation, the assumption of rigid wall was applied. The blood flow was treated as the incompressible viscous Newtonian fluid [18]. The density of the blood and the dynamic viscosity were assumed to be 1050 kg/m^3 and 0.0035 $Pa\cdot s$ respectively.

2.3 The 0D/3D Coupling Method and Coupled Model

The 0D/3D coupled models were built by coupling the 3D postoperative models with the lumped parameters model (LPM, 0D sub-model) of the patient's cardiovascular system. The LPM used in this study was also used in our previous study [17]. The two 0D/3D coupled models shared the same 0D part since the patient's peripheral vascular structure (in opposite to surgical area) didn't change with different grafting. The algorithm of 0D/3D coupling used in this study was also used in some of our previous study [17, 19]. The data exchange between the 3D and 0D part was executed based on each time step. ANSYS-CFX was used to carry out the 3D simulation, while the calculation of 0D part (LPM) was implemented based on CFX Junction Box and CFX User CEL Function. The linear interpolation was applied to make the timeline in 0D calculation and 3D simulation consistent.

3 Results

3.1 The Coronary Artery Flow

3.1.1 The left main coronary artery flow rate

The LM flow rates of two models with different graft were depicted in Fig.2. The low LM flow is caused by the serious stenosis. Moreover the graft type didn't affect the LM flow rate.

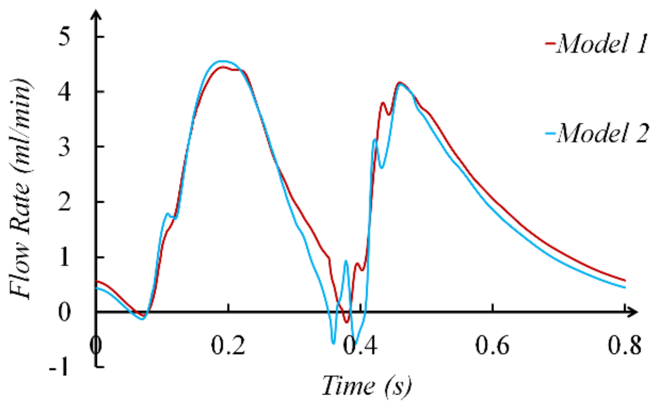

Figure 2: The left main coronary flow rate.

3.1.2 *The left anterior descending artery flow rate*

The LAD flow rates were calculated by summing all the outlet flow of the LAD branches as shown in Fig.3. It can be found from the figure that the LAD flow of the sequential graft is a little higher than the Y-Type graft, but the difference is very small.

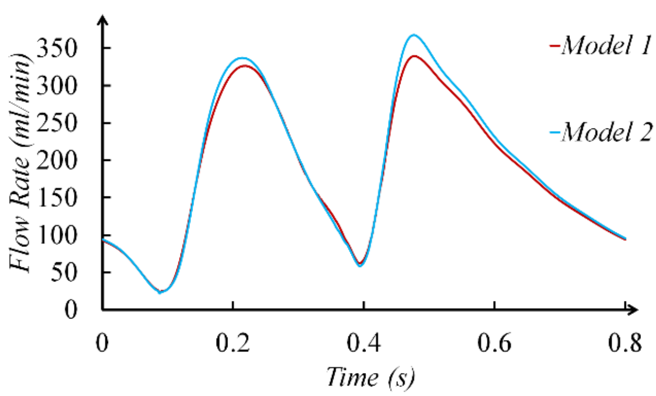

Figure 3: The left anterior descending artery flow rate.

3.1.3 *The left circumflex artery flow rate*

The outlet flow rate of the left circumflex artery (LCX) branches were summed as the LCX flow rate, as illustrated in Fig.4. The LCX flow waveforms of two models are almost the same. In both models, the LCX flow rates are lower than the LAD flow rates.

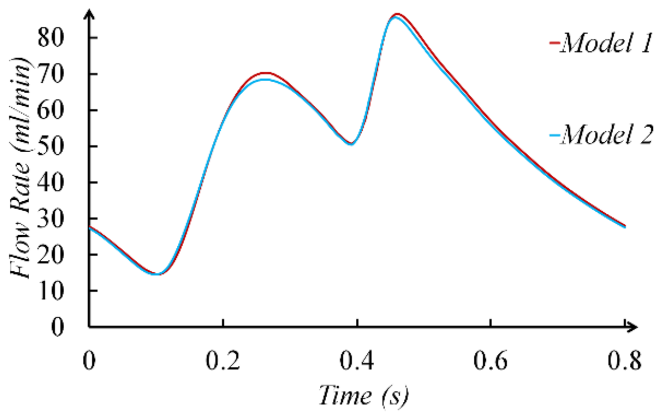

Figure 4: The left circumflex artery flow rate.

3.1.4 The right coronary artery flow rate

The outlet flow rates of the right coronary artery (RCA) branches were summed as the RCA flow rate. The RCA flowrate waveforms were depicted in Fig.5.

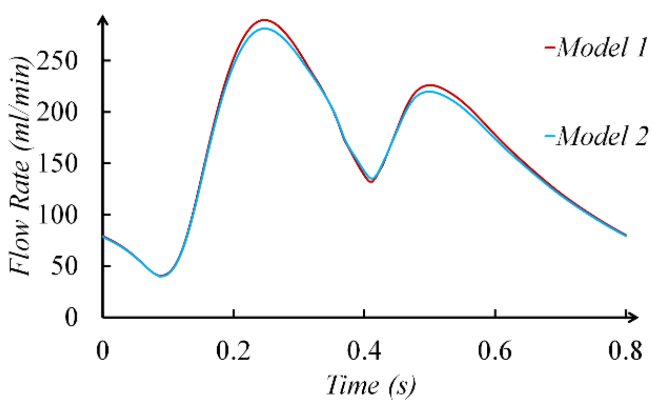

Figure 5: The right coronary artery flow rate.

Finally, the time-averaged LM, LAD, LCX and RCA flow rates were listed in Table 2. It can be found that no significant difference of the coronary flow exist between sequential graft and Y-type graft. The difference of LAD, LCX and RC flow rates between the two models are all within 3%. The LM flow rates of two models are almost the same and very low. All these results show that the coronary flow distribution of sequential graft and Y-type graft are almost same.

Table 2: The coronary artery flow rate (ml/min).

Model	LM	LAD	LCX	RC
1	2.04	184.62	50.30	163.61
2	1.88	190.29	49.68	160.85

3.2 The Graft Flow

Some cross-sections on the grafts in different models were picked out, as shown in Fig.6.

The flow rate through these sections were calculated as the graft flow.

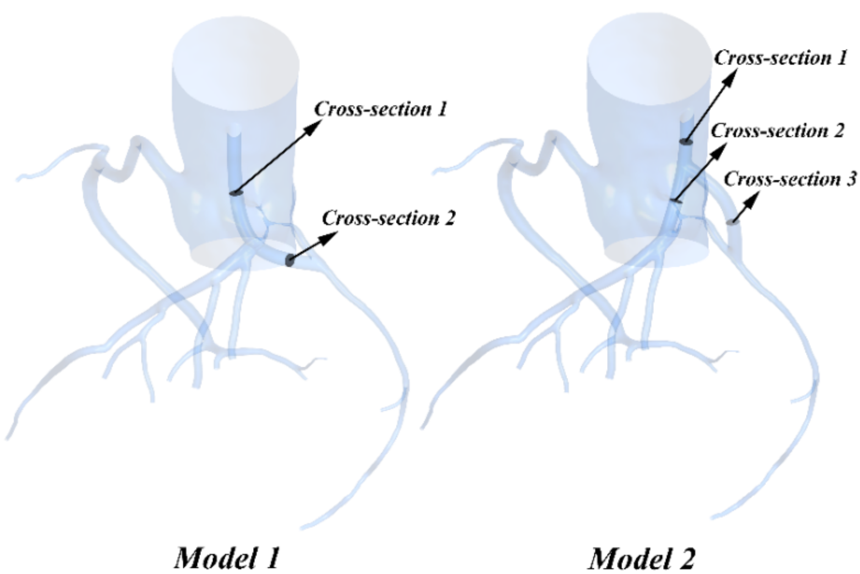

Figure 6: The cross-sections used to calculate the graft flow.

3.2.1 The total graft flow

In both of the models the flow rate through cross-section 1 was treated as the total graft flow. The total graft flows were calculated and the waveforms were depicted in Fig.7.

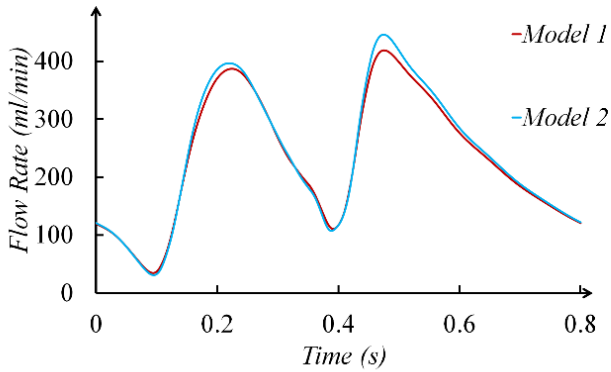

Figure 7: The total graft flow rate.

3.2.2 The graft flow rate to LAD

In Model 1, the difference between the flow rate through cross-section 1 and that through cross-section 2 was treated as the graft flow to LAD. While, in Model 2 the flow rate through cross-section 2 was treated as the graft flow to LAD. The graft flow to LAD of these two models were illustrated in Fig.8.

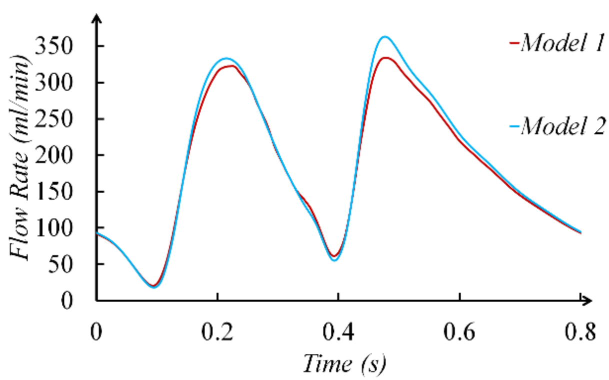

Figure 8: The graft flow rate to LAD arteries.

3.2.3 The graft flow to LCX

In Model 1 the flow rate through cross-section 2 was treated as the graft flow to LCX. In Model 2 the flow rate through cross-section 3 was treated as the graft flow to LCX. The graft flows to LCX were depicted in Fig.9.

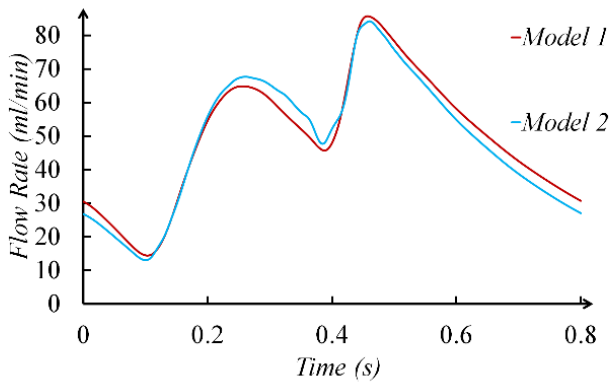

Figure 9: The graft flow rate to LCX arteries.

Finally, the time-averaged graft flow were listed in Table 3. The differences of the total graft flow, the graft flow to LAD and the graft flow to LCX between two surgical procedures are all within 3%. That means the difference of graft flow between two different grafting are not significant.

In general, the short-term outcomes, including the graft flow and coronary flow distribution, of sequential graft and Y-type graft are almost the same.

Table 3: The time-averaged graft flow rate.

Model	Total graft flow	Graft flow to LAD	Graft flow to LCX
1	231.86	182.23	49.62
2	237.41	187.55	48.79

3.3 The Wall Shear Stress

The waveforms of area-averaged wall shear stress (WSS) on the graft were calculated and depicted in Fig.10. The time-averaged WSS on the graft of Y-type graft is 4.45 *Pa*, while that of sequential graft is 5.31 *Pa*. The WSS of sequential graft is 19.1% higher than Y-type graft. Some time-points were picked out and marked in the figure, at which time the area average WSS got the extreme value. The WSS contour at these time points were also listed in Fig.11. Moreover, the low WSS area (<0.4 Pa) at these time points were listed in Table 4. It can be found from the WSS contour and Table 4 that low WSS area exist in both of the models. But the low WSS area on sequential graft is smaller than that on Y-type graft.

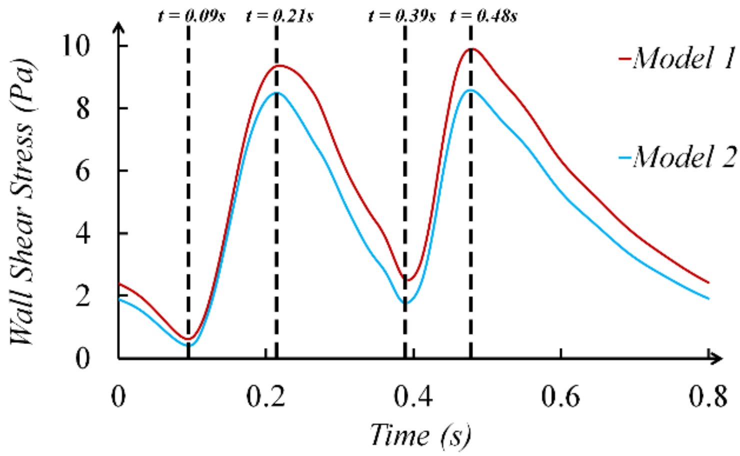

Figure 10: The area average wall shear stress of the graft and the extreme value time.

Table 4: The low WSS area and percentage on the graft.

Time(s)		0.09	0.21	0.39	0.48
Model 1 (411.272 mm^2)	Area(mm^2)	172.833	1.667	13.551	1.338
	Percentage (%)	42.02%	0.40%	3.29%	0.32%
Model 2 (487.120 mm^2)	Area(mm^2)	305.828	2.270	23.702	2.877
	Percentage (%)	62.78%	0.47%	4.86%	0.59%

3.4 The Streamline

The streamline through the graft at several time points were illustrated in Fig.12. The total graft flow got the extreme value at these time points. Flow separation appears at the bifurcation of Y-type graft, while it's much better in sequential graft.

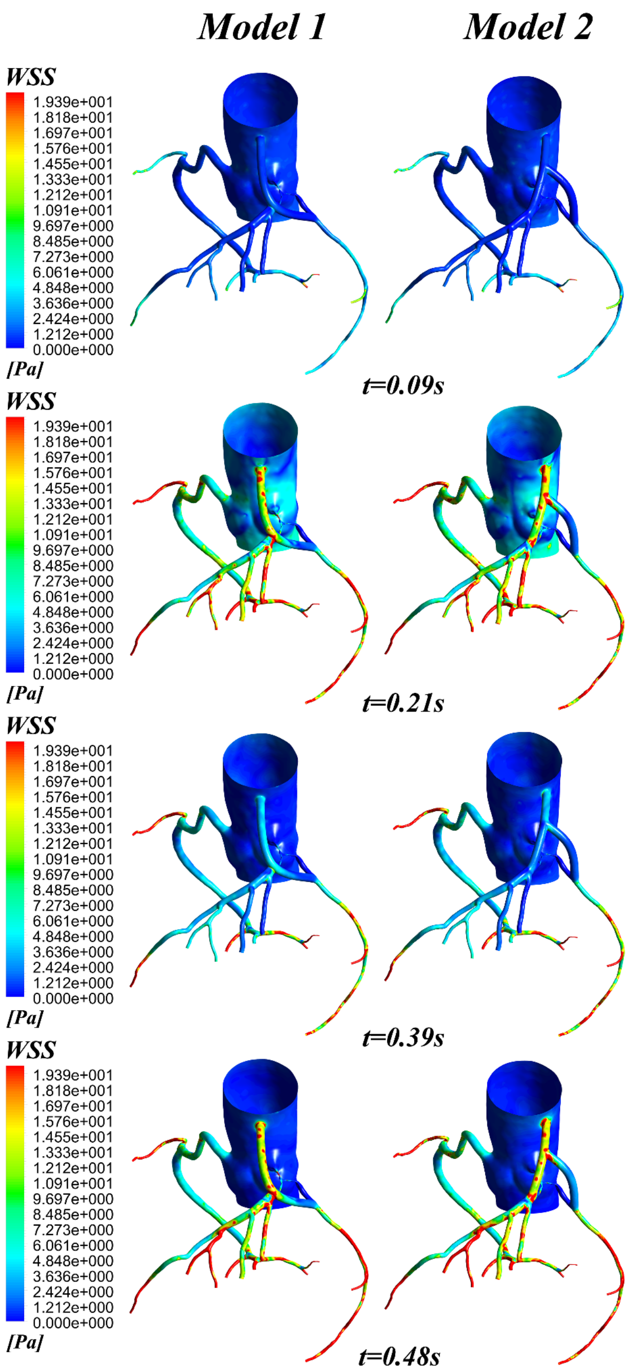

Figure 11: The WSS contour at the extreme value time.

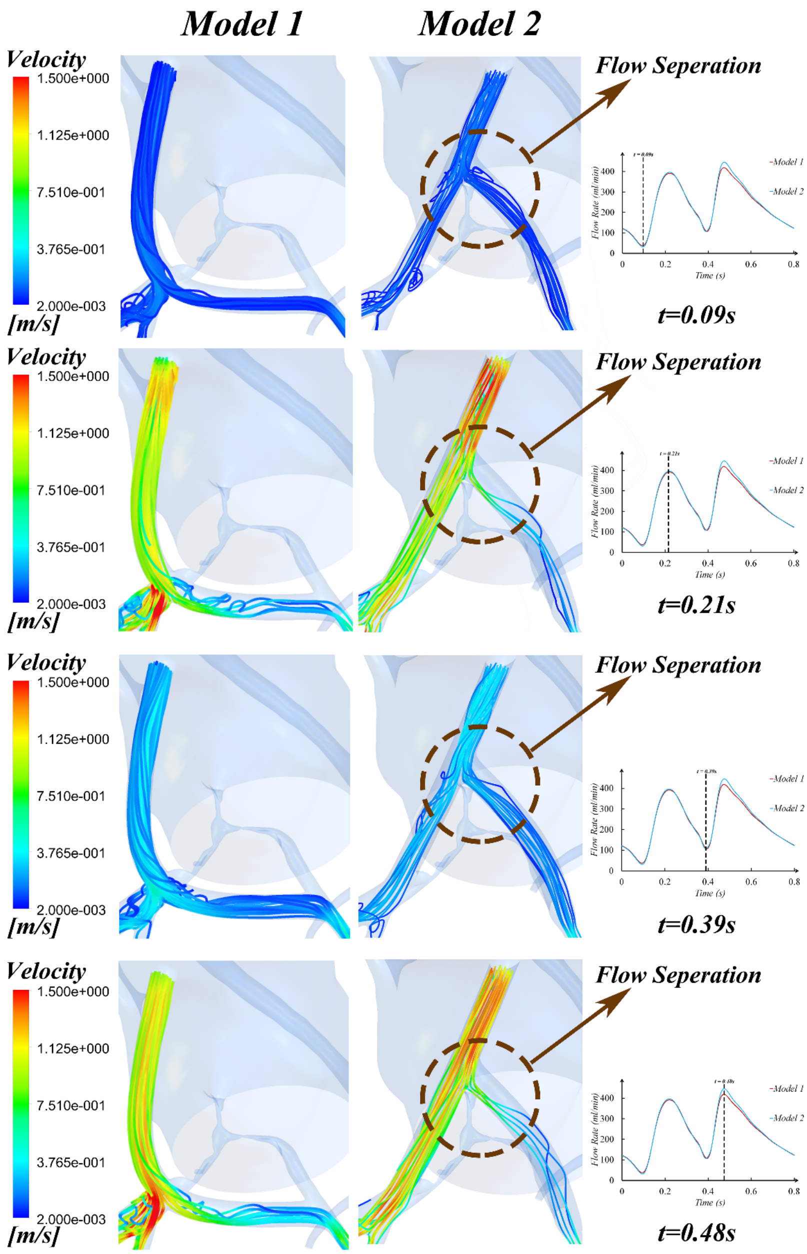

Figure 12: The streamline at the extreme flow rate time.

3.5 The oscillatory shear index

The OSI was calculated according to the expression in equation (1), which on the grafts were illustrated in Fig.13. It can be found from the OSI contour that high OSI area exist in both grafts.

$$OSI = \frac{1}{2}\left(1 - \frac{\left|\int_0^T \overrightarrow{\tau_\omega} dt\right|}{\int_0^T \left|\overrightarrow{\tau_\omega}\right| dt}\right) \tag{1}$$

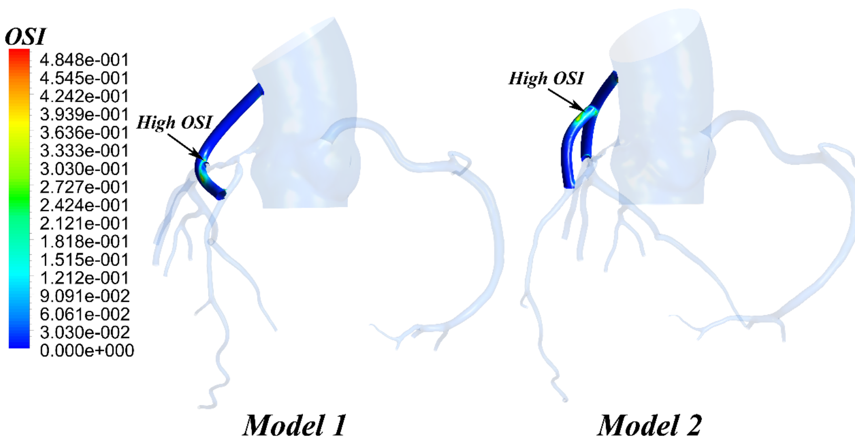

Figure 13: The OSI contour of two models.

4 Discussion

4.1 Short-term outcomes

Results show that no significant difference exist between the sequential graft and Y-type graft. The coronary flow rate is limited by the coronary resistance vessels [20]. Moreover, the resistance of the graft may be lower than the native coronary arteries. So the flow rate of the graft and the flow distribution to LAD and LCX will not change with the graft type. Our previous study shows that the graft flow and flow distribution of Y-type graft and normal graft are also almost the same [17]. Comprehensive considering the results of our previous study and this study, in our opinion, logical surgical procedures may not affect the graft flow and flow distribution.

It can also be found that no significant competitive flow exist in both models with sequential graft and Y-type graft. High competitive flow will produce unbeneficial

WSS distribution associating with endothelial dysfunction and subsequent graft failure. When the stenosis rate is lower than 75%, the probability of competitive flow will be large [21]. The stenosis rate of the model in this study is much higher than 75%, because of this, the LM flow in both models are very low.

In general, the short-term outcomes of sequential graft and Y-type graft are similar and excellent. Studies shows that the short-term outcomes of CABG are generally excellent, but patients remain at risk for future cardiac events due to progression of native coronary disease and/or coronary bypass graft failure [22-25].

4.2 Long-term patency

The low WSS will affect the long-term effectiveness of the surgery [26, 27]. Low WSS area appears on the graft to LCX in both models. Moreover the WSS on the native LCX is much higher than that on the graft to LCX. The low WSS in the graft to LCX was caused by the low velocity. It has been discussed that the graft flow is controlled by the distal resistance vessels. So the flow rate will not decrease with the graft diameter, when it is larger than the native coronary artery diameter [17]. While, the velocity in the graft will increase when the graft diameter decrease. In other words, the diameter of the graft to LCX was too large. So thinner graft should be used to bypass thinner coronary branch, thicker graft should be used to bypass thicker branch. Thus the long-term patency of the surgery might be better. Low WSS and high OSI appear on the graft for both models. Low WSS and high OSI will affect the long-term patency of the graft. But the area-averaged WSS of sequential graft is higher than that of Y-type graft, the low WSS area in sequential graft is smaller than the Y-Type graft. Moreover, the opportunity of vascular intimal hyperplasia at flow separation area is much higher [28]. So the flow separation at the bifurcation of Y-type graft may affect the long-term patency. Y-type graft was usually used for the patient with brittle aorta, surgeon don't want to make more anastomosis on the aorta. Thus, sequential graft might be a good choice instead of Y-type graft for the long-term patency.

5 Limitation

The rigid wall hypothesis was applied in the 3D simulation, which might be the most important limitation of this study. The fluid structure interaction (FSI) [29-31] was not used for two reasons. First, FSI calculation will cost too much time to finish this study. Second, the displacement of the coronary artery cannot be measured. The material properties of the coronary artery might not be the most important factor to affect the simulation result but the displacement of the coronary artery. The reason is that the coronary arteries run on the surface of the heart and move with the heartbeat, the displacement of coronary arteries in one cardiac cycle is large, anisotropic and hard to be measured.

6 Conclusion and Future Work

First, no significant difference exist in the short-term outcomes between sequential graft and Y-type graft.

Second, if a graft with smaller diameter was used to bypass the LCX, the long-term patency of both models will be better.

Third, the long-term patency of sequential graft is better than that of Y-type graft for the low WSS and the flow separation at the bifurcation of Y-type graft. Thus sequential graft might be a better choice for the patient with brittle aorta instead of Y-type graft.

The relationship between the graft diameter and the native coronary arteries will be studied in our future work. The graft with the best diameter can provide enough flow rate and will got higher WSS at the same time.

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Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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