Experimental study on anastomotic hemodynamics using tomographic particle image velocimetry

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Keywords: tomographic particle image velocimetry, anastomosis, hemodynamics, vortex, wall shear stress.

ABSTRACT

Fluid mechanics is an important factor to the failure of the graft anastomosis surgery. In order to better understand the mechanism of restenosis and graft failure of the anastomosis from the perspective of fluid mechanics, an end-to-side silicone anastomosis model with 45° anastomotic angle was used for research. The anastomosis model was connected to a continuous flow loop. where the flow rate can be adjusted during the experiment to simulate several conditions. The tomographic particle image velocimetry (TPIV) was applied to obtain the internal three-dimensional and three-component (3D-3C) flow field. The hemodynamics inside the anastomosis model was quantitatively analyzed based on the averaged 3D-3C flow field. The results present that there are phenomena such as recirculation, spiral flow, flow stagnation, and large vortex structures inside the anastomotic flow field. The oscillation of the recirculation zone size and flow stagnation point indicate the fluid stimulation to the endothelial cells. Also, the double spiral vortex structure could cause high local shear stress, which in turn cause trauma to the red blood cells and lead to local coagulation. Besides, thanks to the 3D-3C flow field, the wall shear stress (WSS) on the entire model wall was obtained, which enables us to predict the mechanical influence to the intimal hyperplasia. The local low WSS was found near the graft toe and recirculation regions, while the local high WSS was found on the host vessel bottom where the jet directly impinges. The abnormal flow phenomena can explain the high-risk regions in the anastomosis, where the stenosis and intimal hyperplasia are prone to appear. The 3D-3C flow field based on the in vitro experiment can strengthen the understanding of the anastomotic restenosis pathology and provide further reference for the surgery improvement.

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1. Introduction

Anastomosis is an important surgical procedure to treat some cardiovascular diseases, such as the coronary artery bypass graft (CABG) to treat coronary artery disease. However, the graft anastomosis faces the risk of restenosis or even occlusion, which is known as graft failure. The graft failure is mainly caused by the intimal hyperplasia (IH), and the researchers found local hemodynamics is an important indication to the IH (Haruguchi & Teraoka, 2003; Kabinejadian et al., 2016). To investigate the hemodynamics of the anastomosis, multiple techniques were applied, such as the non-invasive photochromic dye (Ojha et al., 1990) , planer particle image velocimetry (PIV) (Liu et al., 2020) and computational fluid dynamics (CFD) (Loth et al., 2003). However, the experimental results of three-dimension flow fields are still not enough.

We aim to obtain three-dimensional flow field inside the anastomosis model by using the tomographic particle image velocimetry (TPIV) method. The 3D-3C experimental flow field is better for understanding the hemodynamics of anastomosis and graft failure. Besides, we hope to give references for further medical studies and numerical simulations.

2. Materials and methods

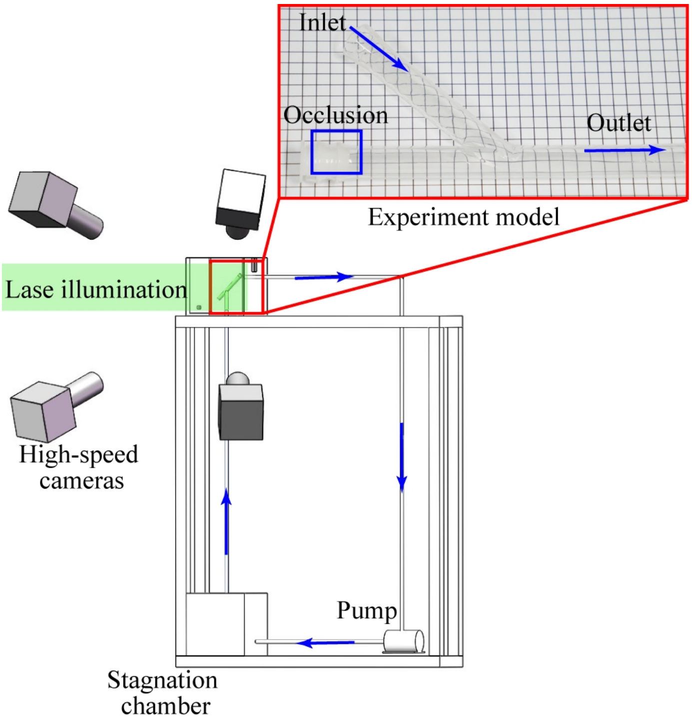

Figure 1. Experiment setup and the anastomosis model.

One 45-degree end-to-side graft anastomosis model made by silicone elastomer was applied as the experimental model shown in Figure 1. The inner diameter D is 10 mm. The glycine-water solution (61 weight percent of glycerin, $\rho = 1150 kg/m^3$, $\mu = 0.0105 Pa \cdot s$), which can match the refractive index of silicone (Buchmann et al., 2011; Xu et al., 2024), was prepared for the experiment. The results of refractive index match are shown in Figure 2 (Xu et al., 2024). The time-resolved tomographic particle image velocimetry (TPIV) technique was applied to capture the flow field inside the anastomosis model. The experiment was carried out in a continuous flow loop (Figure 1) with several flow conditions. The flow conditions are listed in Table 1, where $Re_D = \rho U_{in} D/\mu$.

Table 1. The experimental cases.

Case	Mean inlet velocity U_{in} (m/s)	Re_D
1	0.09	100
2	0.47	500
3	0.77	850

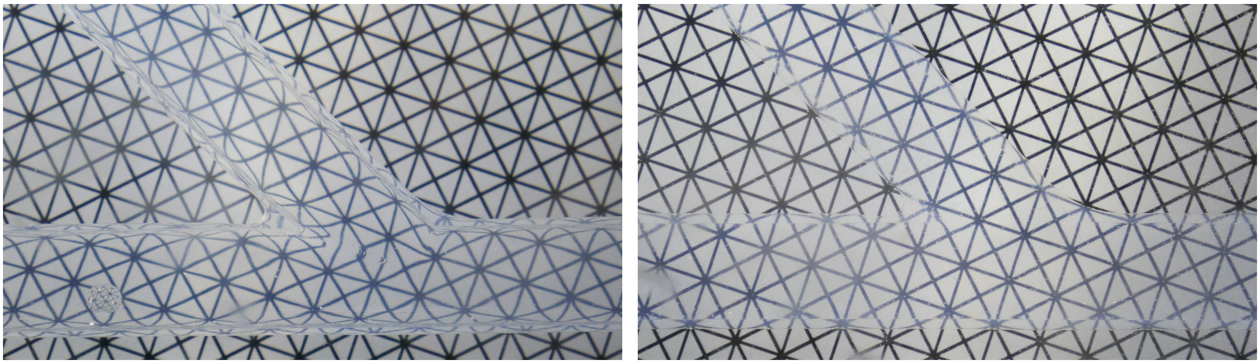
(a)
(b)

Figure 2. Refractive index matching. (a) The model in the distilled water. (b) The model in the water–glycerin mixture solution.

3. Results and discussion

The average velocity fields colored by the non-dimensional velocity U^* ($U^* = \sqrt{u^2 + v^2 + w^2}/U_{in}$) are shown in Figure 3. The flow fields display phenomena such as recirculation zone, stagnation point, spiral flows, etc. As the flow rate increases, the recirculation zone becomes larger and more complex. Also, the inlet velocity profile is gradually skewed towards the toe. In the Case 1, the streamlines are less chaotic compared with those of Case 3. This phenomenon means that the flow field becomes more complex when the flow rate increase. It is expected that during the cardiac cycle, the recirculation zone size and stagnation point location would oscillate with the flow rate changes. The oscillation would stimulate endothelial cells and further cause endothelial dysfunction.

We obtained the vorticity field (Figure 4) based on the average velocity field and the vorticity along x direction is non-dimensionalized ($\omega_x^* = \omega_x D/U_{in}$). The double spiral flow structure can be visualized along the x direction and the vorticity gradually decreases when the flow goes downstream.

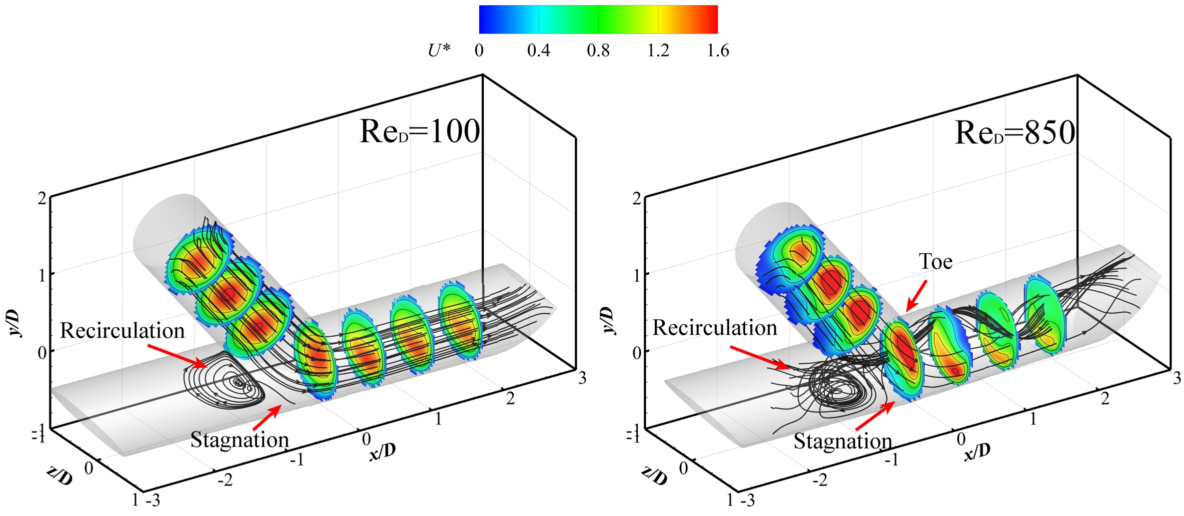

Figure 3. The average velocity fields in the case 1 and 3.

On the one hand, the red blood cells tend to be injured by the shear from the vortex structure, which results in hemolysis phenomenon (Köhne, 2020). On the other hand, the high flow shear caused by vortices can activate platelets and lead to platelet marginalization, thus inducing local coagulation.

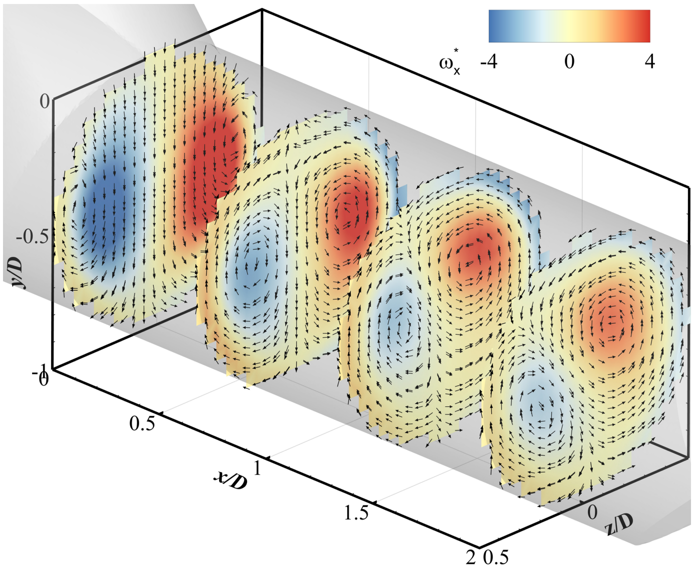

Figure 4. The vorticity field of case 2. The vectors are uniformed to better show the rotational direction.

We calculated the wall shear stress (WSS) of the model inner wall based on experimental data (Gao et al., 2021). The results presented in Figure 5 can clearly show the WSS distribution. Local low WSS is found on the wall of recirculation zone and after the toe. The low WSS can exacerbate the deposition of cholesterol and platelets. The high WSS is found on the host vessel bottom, where the jet directly impacts. The endothelial cells would suffer from their injury and functional problems in the high WSS conditions. The abnormal WSS appearing on the walls indicates the locations where the intimal hyperplasia prone to occur (Sottiurai et al., 1983) and these results should be attached more attentions by the researchers.

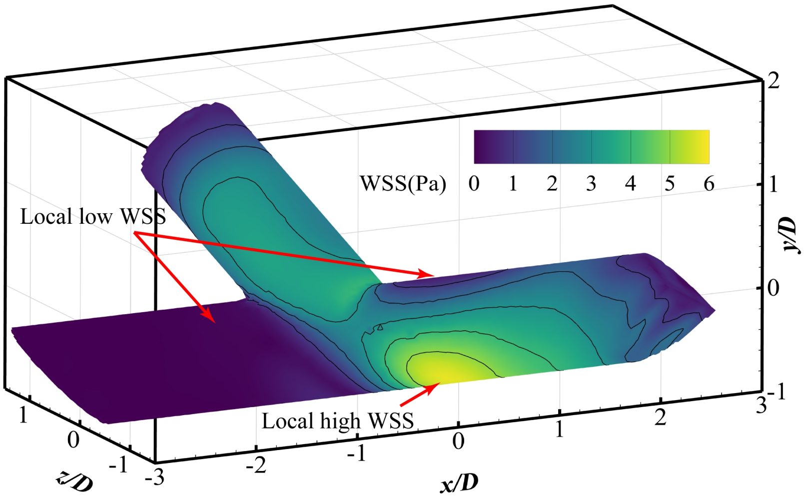

Figure 5. The WSS on the entire model of case 2.

4. Conclusions

The TPIV technique was successfully applied to study the anastomosis hemodynamics in vitro. Benefiting from the three-dimensional measurement results, more detailed information such as the spatial velocity distribution, vortex structure and the WSS on the whole anastomotic model are quantitatively obtained. We think that the results can strengthen the understanding the hemodynamics of the anastomosis and the graft failure.

Acknowledgements

This work was supported by the National Key R&D Program of China (Grant No. 2020YFA0405700) and the National Natural Science Foundation of China (Grant No. 12072320).

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