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Hemodynamic Analysis of a Microanastomosis Using Computational Fluid Dynamics

Shunjiro Yagi,* Takafumi Sasaki,† Takahiro Fukuhara,‡ Kaori Fujii,* Maki Morita,* Yoshiko Suyama,* Kohei Fukuoka,* Teruyasu Nishino† and Ichiro Hisatome§

**Department of Plastic and Reconstructive Surgery, Tottori University Hospital, Yonago 683-8504, Japan, †Cardio Flow Design, Inc., Chiyoda 102-0075, Tokyo, Japan, ‡Division of Otolaryngology, Head and Neck Surgery, Department of Sensory and Motor Organs, School of Medicine, Faculty of Medicine, Tottori University, Yonago 683-8504, Japan, and §Department of Genetic Medicine and Regenerative Therapeutics, Graduate School of Medical Sciences, Tottori University, Yonago 683-8503, Japan*

ABSTRACT

Background Technical issues in free flap transfer, such as the selection of recipient vessels and the positioning and method of anastomosis of the vascular pedicle, have been the subject of vigorous debate. Recent developments in computational fluid dynamics (CFD) have enabled the analysis of blood flow within microvessels. In this study, CFD was used to analyze hemodynamics in a microanastomosis.

Methods In the fluid calculation process, the fluid domain modelizes microvessels with anastomosis. The inlet flow conditions were measured as venous waveform, and the fluid is simulated as blood. Streamlines (SL), wall shear stress (WSS), and oscillatory shear index (OSI) at the anastomosis were visualized and analyzed for observing effects from the flow field.

Results Some flow disruption was evident as the SL passed over the sutures. The maximum recorded WSS was 13.37 Pa where the peak of a suture was exposed in the lumen. The local maximum value of the OSI was 0.182, recorded at the base of the anastomosis on the outflow side.

Conclusion In the ideal anastomosis, the SL is disrupted as little as possible by the sutures. The WSS indicated that thrombus formation is unlikely to occur at suture peaks, but more likely to occur at the base of sutures, where the OSI is high. Tight suture knots are important in microanastomosis.

Key words computational fluid dynamics; computational modeling; microsurgery; reconstruction; sutured

Advances in the surgical instruments, suture threads, and microscopes used in microanastomosis formation and developments in anastomosis techniques means that free flap transfer has now been established as a comparatively safe surgical procedure. However, many studies have found that the free flaps used for reconstruction in the head and neck region have a vascular patency rate of almost 100%,[1–3] while most studies of free skin flap transfer to treat injuries in the limbs report a rate of only around 95%.[4, 5] This may be because limb vessels often suffer degeneration due to arteriosclerosis, making the endovascular walls susceptible to damage, or because the choices of recipient vessels are limited, meaning that it is often necessary to join the vascular pedicle of the skin flap with vessels of very different diameters. Although modifying the method of anastomosis can enable anastomosis formation between vessels of different diameters, this has the problem of requiring that the sutures used for anastomosis to be tied off more often. Though it is certainly necessary to fit both intima exactly, exposed sutures within the vascular lumen affect hemodynamics, and they may contribute to post-anastomosis thrombus formation. There have been no reports evaluating what kind of influence threads in the lumen give to blood flow. In this study, computational fluid dynamics (CFD) was used to analyze the fluid dynamics in a microanastomosis and investigate the effect of sutures on blood flow passing through a microanastomosis.

MATERIALS AND METHODS

To increase the effect of the sutures on blood flow, this anastomosis simulated the tapering technique.[6] A model vascular anastomosis 2 mm in diameter was used. Computational meshes were created using commercial meshing software (ANSYS ICEM16.0, ANSYS Japan, Tokyo, Japan). The mesh has 700,890 elements and 198,467 nodes (Fig. 1).

The suture thread used had a diameter of 0.03 mm (equivalent to 10–0 nylon). Ten stitches were inserted around the circumference of the vessel, with the thread extending into the lumen at a height of 0.025 mm and length of 0.115 mm. On the outflow side, three sutures

Corresponding author: Shunjiro Yagi, MD, PhD
yagishun68@gmail.com
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Abbreviations: CFD, computational fluid dynamics; OSI, Oscillatory shear index; PISO, Pressure-implicit with splitting of operators; SL, streamline; WSS, wall shear stress

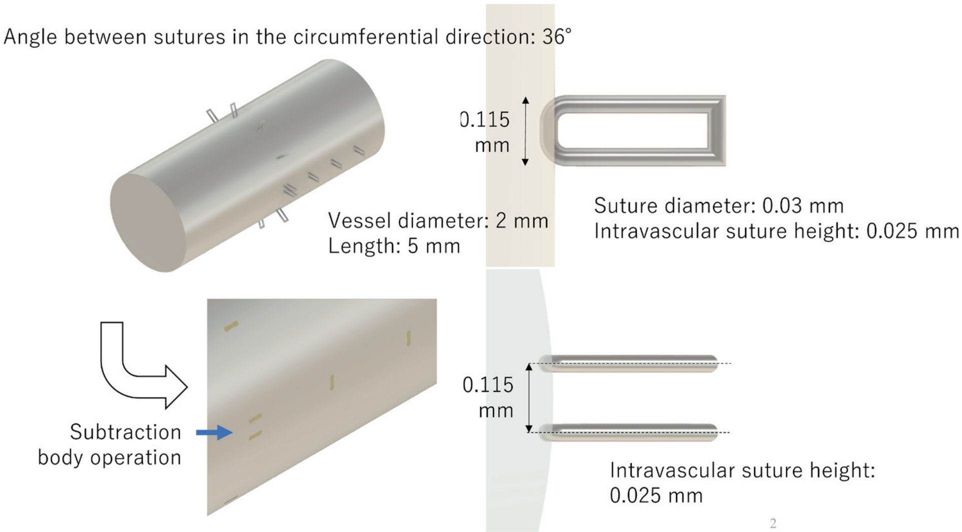

Fig. 1. Suture modeling process. Both the inlet and outlet vessels were 2 mm in diameter. The sutures were aligned at a 36º angle, and stitches were inserted in 10 places. At the site simulating the three-point anastomosis, however, two sutures were inserted parallel to each other (arrow).

were placed in a single row. In the part corresponding to the three-point suture, the sutures were aligned in parallel, 0.115 mm apart. The computer-aided design (CAD) model was created by using commercial software (Fusion 360, Autodesk, Mill Valley, CA).

Inlet blood flow was created using an ultrasound flowmeter (HT323 surgical flowmeter, Transonic Systems, Ithaca, NY. Its probe size was 2.0 mm) with a period of 1.0 s, based on the venous waveform.[7] This was set up so that the maximum value was 45.0 mL/min at 0.14 s, the minimum value –19.0 mL/min at 0.84 s, and the mean flow volume was 13.0 mL/min (Fig. 2). The pressure gradient at the outlet was stipulated as zero, and the wall surface was given a no-slip condition.

The CFD analysis conditions were as follows. OpenFOAM v5.0 software was used for analysis. Turbulent pulsatile flow simulation is performed with reference to previous hemodynamic research as follows. The software solves the Navier–Stokes equations of incompressible transient Newtonian fluid. The time step size was set up at 5.0 times for 5-10 seconds to reduce the Courant number to the sufficient level. We also set 5–10 seconds as the convergence criteria, where the residual at each time step was timed. The fluid density was set at 1,060 kg/m^3, the coefficient of viscosity was set at 0.004 Pa-s to simulate blood.[8, 9]

Streamlines (SL), wall shear stress (WSS), and oscillatory shear index (OSI) are visualized and analyzed by using CFD postprocessing software (ParaView, Kitware, NY). The WSS is calculated as velocity gradient by using longitudinal velocity, distance from the wall, and the viscosity. In other words, it is the frictional

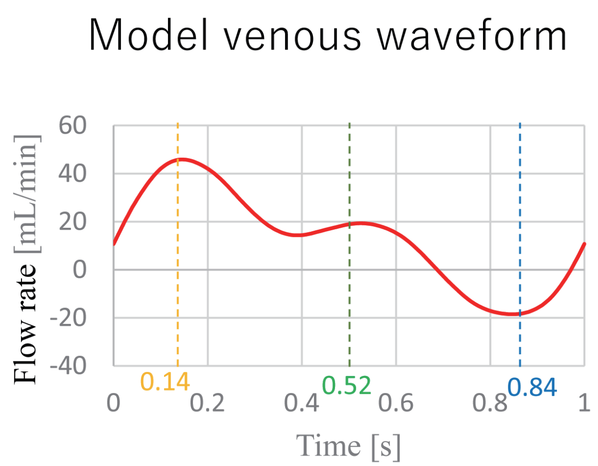

Fig. 2. Model venous waveform. It was set up so that the period was 1 s, maximum flow was 45.0 mL/min, minimum flow was –19.0 mL/min, and mean flow was 13.0 mL/min.

$$\mathrm{OSI} = \frac{1}{2}\left[1 - \frac{\left|\int_0^T wss_i dt\right|}{\int_0^T |wssi| dt}\right]$$

Fig. 3. Formula for calculating the oscillatory shear index (OSI).

force exerted by the blood on the vascular wall measured in Pa (N/m^2). The OSI expresses the size of the changes in direction and magnitude of the WSS. It thus indicates the degree of reversing direction of the WSS within a single pulse cycle (Fig. 3).

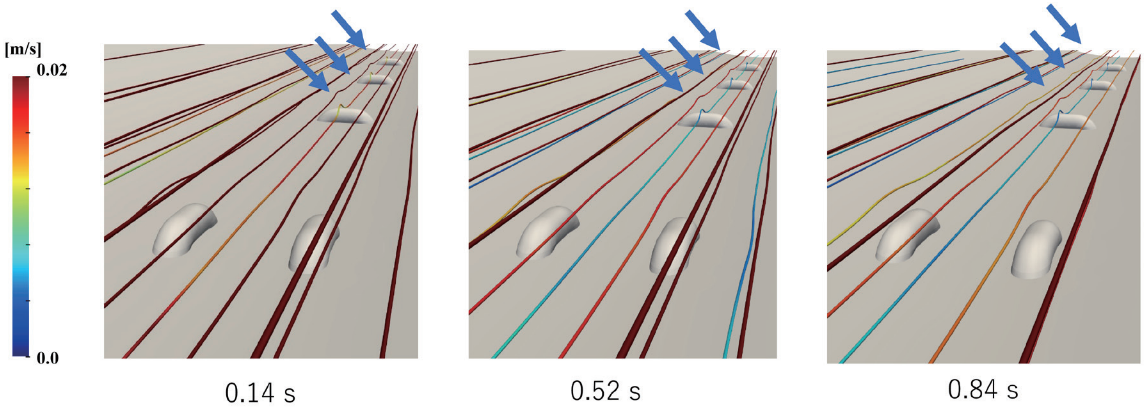

Fig. 4. Stream line (SL). Overall, there was almost no disruption of the SL, but a small amount of disruption was evident when it passed the three sutures (top right) lined up in a row on the distal side (arrows).

RESULTS

Some flow disruption was evident as the SL passed over the line of three sutures on the distal side. Overall, however, the SL was flowing in almost a straight line at all time points (maximum flow at 0.14 s, second flow peak at 0.52 s, and minimum flow at 0.84 s) (Fig. 4). The maximum WSS is measured on the top of the suture at 0.14 s, when the inflow velocity is the peak. (Fig. 5). The local maximum value of the OSI was 0.182, recorded at the base of the anastomosis on the outlet side. However, overall, there were no major differences between the values at different times (Fig. 6).

DISCUSSION

Free flap transfer using microsurgery has become an essential surgical procedure for reconstruction at various sites, such as the head and neck region and the limbs.[1–5] Almost all studies have reported flap survival rates exceeding 95%, and this is regarded as a comparatively safe procedure. In most cases, vessels anastomosed to the free skin flap are around 1–3 mm in diameter, and if anastomosis is performed using a microscope, this is not a very technically difficult procedure. However, in the rare event of thrombus formation at the anastomosis site, in case it is impossible to salvage the grafted flap, another skin flap transfer is required. In the case of reconstruction following malignant tumor resection in particular, delay in starting postoperative adjuvant therapy is extremely detrimental to patients. Since the success or failure of vascular anastomosis has a major effect on patient prognosis, a 100% success rate must be the goal.

One factor that increases the difficulty of microanastomosis is the size discrepancy between the anastomosed vessels. The tapering technique[6] is one method of anastomosing vessels with significantly different diameters. This involves cutting the resection margin of the larger vessel at an angle and suturing it into a funnel shape to reduce its diameter. Although this is an effective technique for use in the microanastomosis of vessels of different sizes, it creates a three-point suture site. In addition, a larger excess of the suture thread used to suture the angled part is required than in a normal end-to-end anastomosis. To prevent blood from leaking at the three-point suture site, the threads must be sewn close together. All of these factors may contribute to post-anastomosis clot formation.

Recent developments in diagnostic imaging and computer simulation techniques have enabled the use of CFD. Most reports of the use of CFD have concerned its use to analyze the occurrence, growth, and rupture

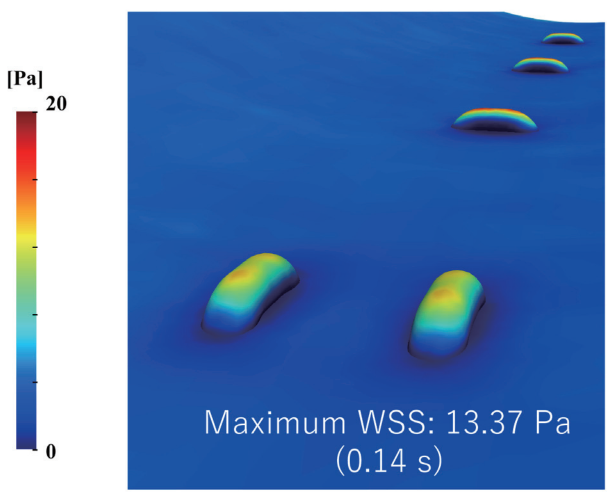

Fig. 5. Wall shear stress (WSS). The maximum value of 13.37 Pa was recorded at 0.14 s.

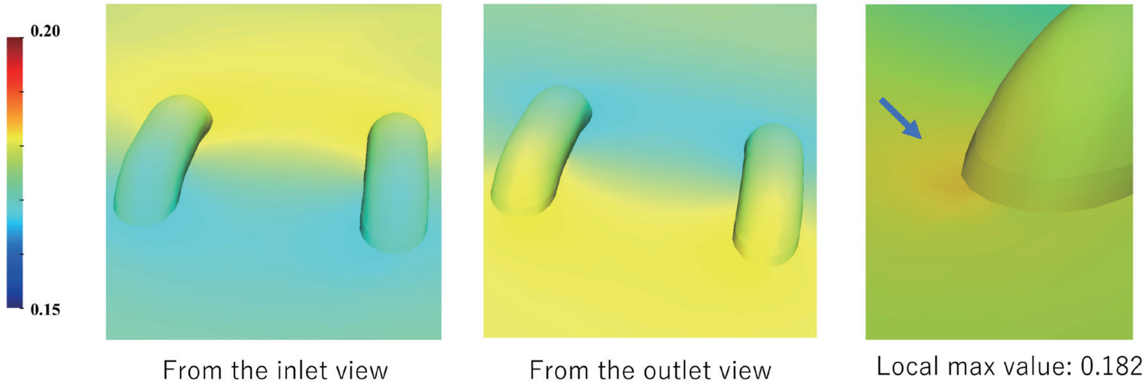

Fig. 6. Oscillatory shear index (OSI). The local maximum value was 0.182 at the base of the anastomosis on the outlet side (arrow).

mechanism of cerebral aneurysms.[10–12] Wain *et al.* used CFD to show that, in a case of microanastomosis 1 mm in diameter, the WSS was greater and SL disruption less when they were sutured than when a coupling device was used.[13] Although the extent to which ST disruption affects clot formation is unclear, it is believed to have at least some effect. The results of the CFD analysis in the present study showed that SL disruption occurred close to the line of sutures on the distal side of the blood flow. This suggests that complex or loose knots might further increase SL disruption. WSS is known to suppress clot formation.[14] Because WSS is a force that acts perpendicularly to the blood vessel, even if a clot were to form near the peak of a suture, it would immediately be detached by the blood flow, making clot formation less likely to occur.

The OSI, another important CFD parameter, was also analyzed. A high OSI is believed to contribute to the generation of oxygen free radicals.[15] Vascular endothelial cells suffer severe oxidative stress during post-ischemia reperfusion,[16] and it is likely that damage to vascular endothelial cells by oxygen free radicals is related to clot formation. In the present simulation, the OSI was highest near the base of the sutures. If a loose knot made the thread higher at a certain place, the area close to the suture base would be prone to clot formation. Because the flow of venous blood reverses with the beating of the pulse, during its return it collides with the anastomosis generating eddies. This may be why the value was particularly high on the outlet side. Arterial blood basically flows in one direction, and the OSI should therefore be comparatively lower at arterial anastomosis than at venous anastomosis. This may be one factor in the greater likelihood of clot formation at venous microanastomosis than at arterial microanastomosis.

CFD has limitations in presenting vital phenomena, but it may be able to increase accuracy by measuring the shapes of vessels and blood flow more clearly to attain preferred conditions.

In conclusion, CFD analysis of blood flow through a microanastomosis showed that the OSI was high at the base of the sutures used for anastomosis, suggesting that this site may be susceptible to post-anastomosis clot formation. Tight, careful knots are required to prevent post-anastomosis clots.

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The authors declare no conflict of interest.

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