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Numerical simulations of different configured venous anastomosis in microvascular flap transfer

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ABSTRACT

Background: Free flap surgery is a well-established method for covering large defects in the head and neck region. Most cases of flap failure are caused by venous thrombosis. Thus, there is a lot of discussion about the ideal design of venous anastomosis and its impact on the hemodynamics in the vessels. This study concentrates on the simulation of flow patterns of different designs of venous anastomoses.
Methods: First, fluid flow rates were measured using transit-time flow measurement in the veins of 20 patients who received free flaps between 2016 and 2017. Five different designs of porcine anastomoses were scanned using micro-computed tomography, to create three-dimensional models. In the second step, numerical simulations of the blood flow were performed to gain insights into the vessel flow patterns.
Results: The simulations revealed recirculation areas in the 60° and 90° end-to-side anastomoses, especially in combination with low fluid flow rates. In addition, there were large areas of recirculation in the 1:3 end-to-end anastomoses.
Conclusion: The type of venous anastomosis should be decided individually. End-to-side anastomosis can be recommended in cases with high caliber differences or in those with high venous outflow. End-to-end anastomoses should be preferred in conditions with low venous outflow.

1. Introduction

In head and neck tumor surgery, we are often confronted with major defects that cannot be treated via primary closure. With a success rate of more than 95%, different free flaps became a reliable method of reconstruction (Bootz et al., 1994; Yang et al., 1997; Bui et al., 2007). However, the improvement of surgical techniques and postoperative surveillance is not able to completely eliminate failures after microvascular flap transfer. Venous anastomotic failures with thrombosis are described as one of the most common complications of free flap failure (Kroll et al., 1996; Chalian et al., 2001; Yu et al., 2009). A thrombosis formation is dependent on many aspects and not fully understood yet. Different causes have already been described at the end of the 19th century by Virchow, who named stasis, vessel damage, and hypercoagulability as the three main factors responsible for the formation of thrombosis. All three factors apply to a venous anastomosis between the donor and recipient side of the vessel and have been evaluated before (Encke, 1977; Esmon, 2009).

Although arterial re-anastomosis in head and neck reconstruction is usually performed end-to-end (ETE) to an external carotid branch, there are multiple options concerning the venous side of the flap. To reduce anastomosis failure, the different possible designs of venous anastomosis have been the focus of many clinical investigations (Chalian et al., 2001; Hanasono et al., 2010; Ahmadi et al., 2014, 2017; Chen et al., 2014; Heidekrueger et al., 2017). ETE and end-to-side (ETS) anastomoses have been compared, as well as two vs. one vein anastomoses, with an ongoing discussion regarding which technique is superior.

Stasis, as one of the main thrombosis parameters, can be influenced by vessel size, suture techniques, and geometric design of the

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anastomosis. To avoid stasis or areas of recirculation, it is important to obtain detailed information about the specific flow attributes as a function of the different types or designs of an anastomosis. To our knowledge, there is no information about these flow attributes in venous anastomosis after microvascular flap transfer yet. For this reason, we focused on gaining important data to improve our understanding of the fluid dynamics in such a setting.

The first objective of this study was to measure the volume flow in the venous vessels before and after the anastomosis, and the second, to use these parameters in simulations of the different types of anastomosis geometry.

2. Patients and methods

2.1. Patient population

This study was primarily approved by the local ethics committee (EK 285-15). Written informed consent was obtained from all patients. The study population consisted of 20 consecutive patients who underwent free flap surgeries in the Department of Oral Maxillofacial Surgery at the University Hospital Aachen between July 2016 and March 2017. The inclusion criteria were all patients who needed reconstructive surgery with a microvascular flap transfer. The exclusion criteria were pregnant women and people who were younger than 18 years.

2.2. Methods

2.2.1. Intraoperative flow measurement

To achieve our first goal of assessing the different flow parameters, two examinations of the free flap vein were done intraoperatively with the VeriQ™ (Medistim, Oslo, Norway) ultrasonic Doppler device (Fig. 1). The first one was performed before raising the flap and the second examination was performed 30 min after the completed anastomosis. The VeriQ™ ultrasonic Doppler device is a common and well-established tool for transit-time flow measurement in coronary artery bypass grafting (Nordgaard et al., 2010). It has three standardized gauge heads for vessel diameters of 1, 2 and 3 mm, which perfectly matches with the average diameter of veins in free flaps (Shima et al., 1996). All the examinations were supervised by the same investigator (J.W.) and the anastomoses were performed by two senior surgeons of the Department of Oral Maxillofacial Surgery at the University Hospital Aachen. Microsoft Excel™ (Microsoft, Redmond, USA) was used to generate mean flow rates with its standard deviations. For the analysis of ETS anastomosis, the flow rate of the internal jugular vein is needed and was extracted from previous literature. These flow rates range from 302 (±218) ml/min to 438 (±226) ml/min for a single jugular vein or from 793 (±276) ml/min to 799 (±288) ml/min for both the jugular veins (Brunholzl et al., 1990; Muller et al., 1990). In our simulation, we used an average flow rate of 400 ml/min for a single jugular vein.

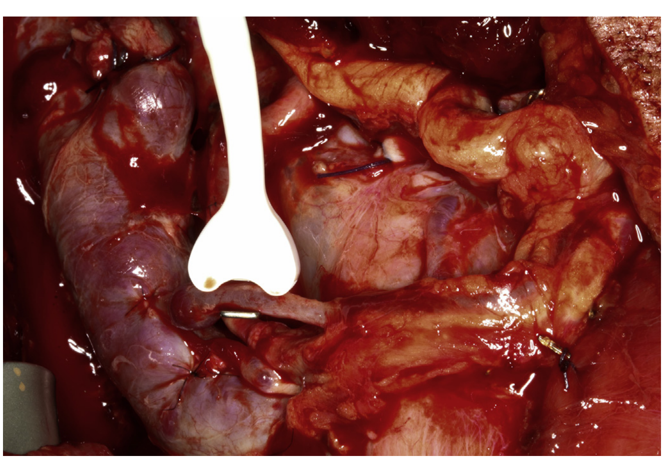

Fig. 1. Intraoperative flow measurements.

2.2.2. Vessel model

Real vessel structures, especially after anastomosis, are not comparable to perfect tubes because they contain projecting parts of sutures or other disturbing unevenness. Although we see a considerably smooth vein to vein contact from the outside, the never-perfect geometric symmetry of the two vessels and the irregularities caused by the sutures might cause disturbed laminar flow. For this reason, fresh porcine veins of the neck, like the internal jugular or the facial vein, were used to create an exact model of the vessels and anastomoses. Four different designs of microsurgical anastomosis were sutured, to generate five 3D models. All of them had different angles and calibers. Two of these anastomoses were ETS and two were ETE. The proportions of the ETE calibers were 1:3 and 1:1. The angles of the ETE anastomoses were 90° and 60°. The stitches were done with an 8-0 monofil non-absorbable polyamide material (Ethilon™, Ethicon, Somerville, USA). To simulate blood filling, the vessels were filled up with a light-body dental impression material (Impregum™ Penta Duo-Soft™, 3M, Saint Paul, USA). After complete curing time, one micro-CT of each model was performed to obtain consistent 3D models for the different types of anastomoses (Fig. 2). Each micro-CT scan was used to extract the geometry of the vessel using Mimics (Materialise, Leuven, Belgium) in order to create virtual 3D models (Fig. 3). To generate the fifth model of a 3:1 anastomosis the virtual 1:3 model was mirrored in its horizontal axis. These five models were then used to perform numerical simulations.

2.2.3. Numerical simulations

Each vessel model was meshed with approximately 20 million tetrahedral cells. The simulations were assumed to be steady and were within a laminar flow regime (inflow Re ≈ 450). Blood was assumed to be non-Newtonian using a Carreau model (Johnston et al., 2004).

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)\left[1 + \gamma^2\lambda^2\right]^{\frac{n-1}{2}} \qquad (1)$$

where $\eta = \textit{local viscosity}\left[\frac{kg}{ms}\right]$, $\gamma = \textit{local shear rate}\left[\frac{1}{s}\right]$, $\eta_\infty = 0.00345\left[\frac{kg}{ms}\right]$, $\eta_0 = 0.056\left[\frac{kg}{ms}\right]$, $\lambda = 3.313\,[s]$, and $n = 0.3568$. The density was assumed to be 1060 kg/m^3.

For each case, the inflow boundary condition was defined with a mean mass flow rate of 6 ml/min, a maximum mass flow rate of 24 ml/min and a minimum mass flow rate of 1 ml/min as described in Fig. 3. For the jugular vein, we defined 400 ml/min as the mean mass flow rate, all outlets being defined with a pressure of 0 Pa. A segregated pressure-velocity coupling solver was implemented with the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm. The spatial discretization for pressure and momentum were second order and second order upwind, respectively. The scaled convergence criteria were set at 10^{-4} for continuity and x/y/z velocity.

3. Results

All patients received a microvascular flap transfer, as a reconstruction after resection of squamous-cell carcinoma. There were

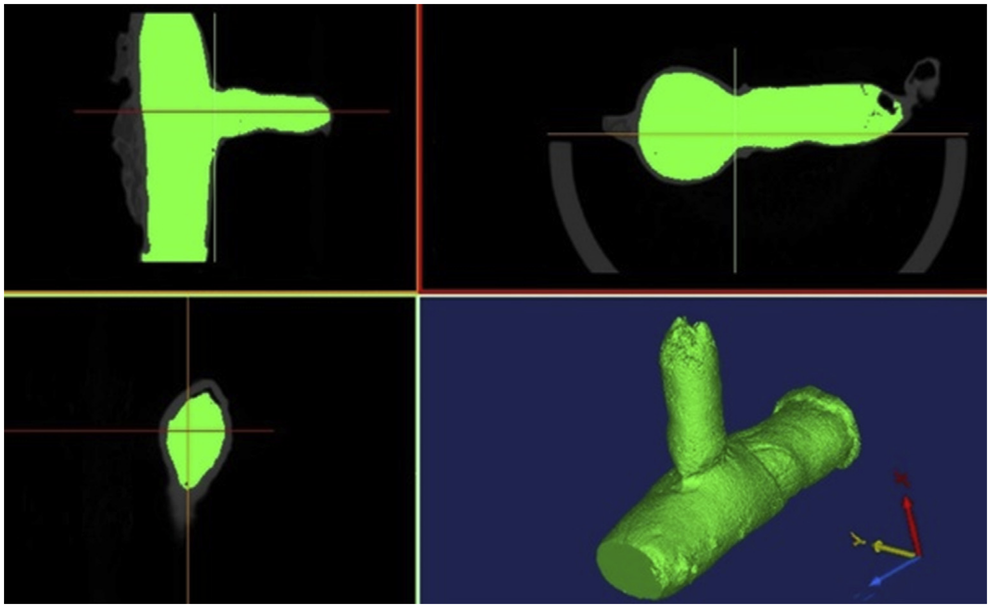

Fig. 2. Micro-computed tomography-scan of the 90° ETS Anastomosis.

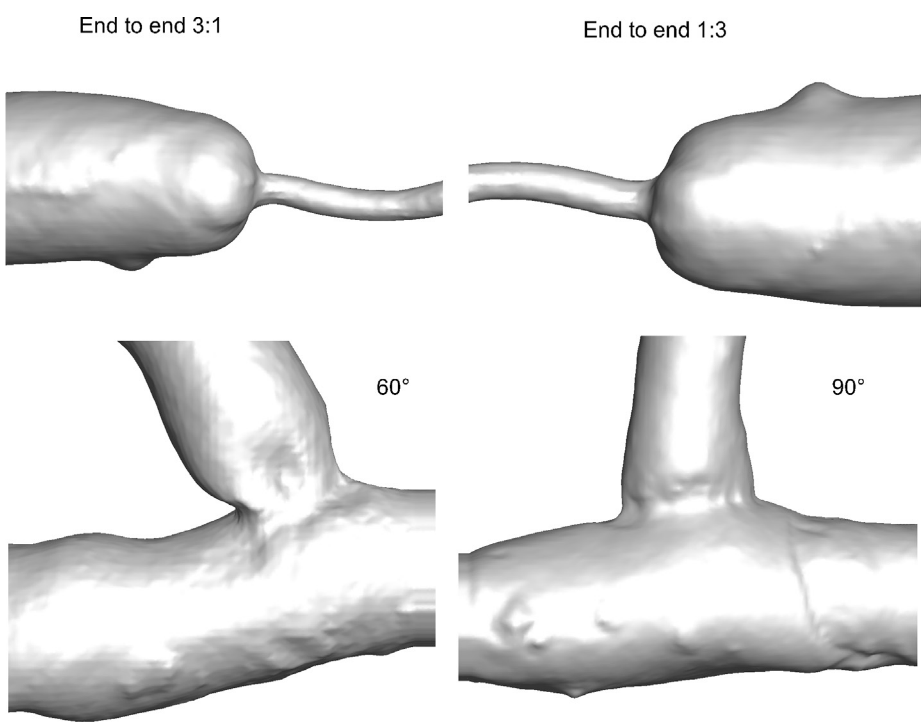

Fig. 3. Three-dimensional models of different designs of microsurgical anastomoses.

seven patients with tumor of the alveolar crests and six cases with tumors at the base of the tongue. Three patients had carcinoma at the floor of the mouth and there were two patients with carcinoma of the margin of the tongue. The last two patients had malignant extraoral tumors. Nine patients were male and 11 patients were female. The average age was 67.9 years. 14 patients had a history of nicotine abuse and four patients had undergone prior radiotherapy. Ten patients received an anterolateral thigh flap (ALT), six patients were treated with a radial forearm flap, and four patients received a fibula flap. In 15 cases, a venous ETS anastomosis to the internal jugular vein was performed. Five ETE anastomoses were performed for local veins. The arterial anastomoses were performed ETE to the facial or the superior thyroid artery. The complete demographic and clinical data of the participants are shown in Table 1.

The free flap transfer was successful in 19 cases. One patient needed flap revision. Thus, the free flap success rate was 95% in the study population, which is consistent with the frequently published success rates for microvascular free flap transfers (Bootz et al., 1994; Yang et al., 1997). The mean flow rate was 4.2 ml/min prior to anastomosis with a standard deviation of 3.4 ml/min. After anastomosis, the mean flow increased non-significantly ($p = 0.249$) to 6 ml/min with a standard deviation of 6.2 ml/min. The minimum

Table 1
Clinical data of the participants.

Number of patients	20
Male	9
Female	11
Average Age (years)	67,9
Nicotine abuse	14
After radiotherapy	4
ASA I	0
ASA II	12
ASA III	8
ASA IV	0
ASA V	0
Recipient vessel for anastomosis:	
Internal jugular vein	15
Facial vein	4
Thyroidal vein	1
Microvascular flap:	
Anterior Lateral thigh (ALT)	10
Radial forearm flap	6
Fibula flap	4
Localization of squamous-cell carcinoma:	
Alveolar crest	7
Floor of the mouth	3
Margin of the tongue	2
Extraoral	2
Base of the tongue	6

flow rate before and after anastomosis was 1 ml/min and the maximum flow rate was 24 ml/min. Both the extremes were found in an ALT flap. The maximum mean flow after anastomosis was also measured in ALT flaps and found to be 8.3 ml/min. In these flaps, the highest difference occurred between the flows before (2.7 ml/min) and after anastomosis. In these distinct cases of ALT flaps, the increase of the mean volume flow rate was significant ($p = 0.046$). The complete data is shown in Fig. 4.

Regarding the numerical simulations, we were able to visualize the volume flow in all different conditions (Figs. 5 and 6). The fluid flow exposed variations in the different types of anastomoses. The fluid velocities (m/s) were the lowest in the simulation with a minimum flow rate of 1 ml/min and consistently increased with the mean rate of 6 ml/min and the maximum flow rate of 24 ml/min. The velocities increased with increasing vessel thickness and flow rate. The highest velocity of 0.6 m/s was found in the 3:1 ETE or rather the 1:3 ETE anastomoses in the simulation with a flow rate of 24 ml/min. The lowest velocity was measured at 0.1 m/s in the 1:1 ETE anastomosis. There were no signs of recirculation in the 3:1 ETE and the 1:1 ETE anastomoses in all of the three inlet volume conditions. Regarding the ETS anastomoses of 60° and 90°, no area of recirculation could be observed with a free flap inflow of 24 ml/min. However, we found small areas of reverse fluid flow in the 60° ETS anastomosis with the minimum flow rate of 1 ml/min and further areas of recirculation in the 90° ETS condition with simulation free flap inflow of 6 ml/min and 1 ml/min. In these cases, the largest extent of recirculation occurred for an inflow of 1 ml/min. Regarding the 1:3 ETE anastomosis, the areas of recirculation occurred for volume flows of 6 and 24 ml/min directly behind the anastomosis at the beginning of the larger caliber. The vortex size was dependent on the flow rate (Figs. 6 and 7).

4. Discussion

Many clinical efforts have been made to find the ideal geometric design or the ideal number of venous anastomoses (Chalian et al., 2001; Hanasono et al., 2010; Ahmadi et al., 2014, 2017; Chen et al., 2014; Heidekrueger et al., 2017). Nevertheless, there is only limited knowledge about the specific flow patterns and hemodynamics inside the anastomoses. In this study, we first focused on gaining realistic venous flow parameters after microsurgical vessel anastomosis. Secondly, we used this data for numerical simulations. These simulations aimed to identify potential irregularities in the venous flow patterns and to support the finding of the ideal design of anastomosis. To achieve the first goal of this study, we used TTFM in venous anastomosis of free flaps in the head and neck region for the first time. Our experience shows that it is an eligible and easy method for gaining information about the venous volume flow rate.

In combination with the clinical evaluation and the use of intraoperative micro-light guide spectrophotometry, it might have a helpful additional safety benefit. Further research is needed to prove this theory. Our measurements showed flow rates with a range of

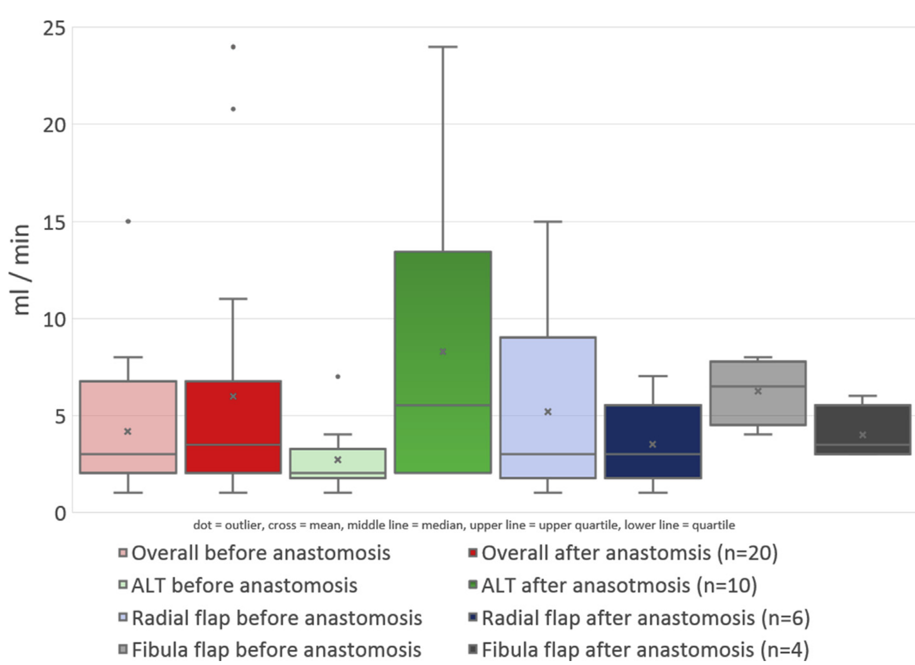

Fig. 4. Venous flow rates before and after anastomosis.

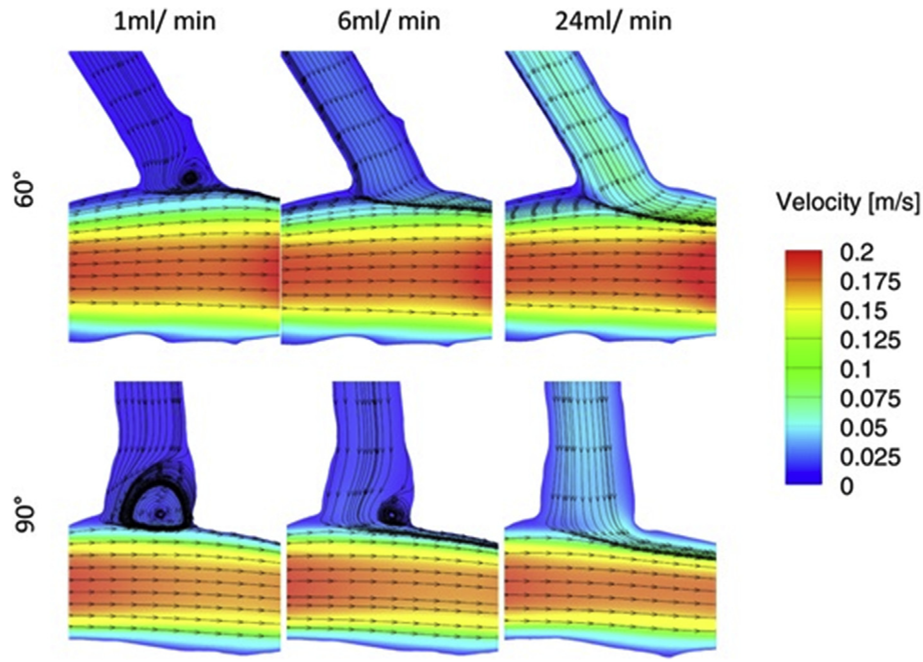

Fig. 5. Flow simulations of the ETS Anastomoses.

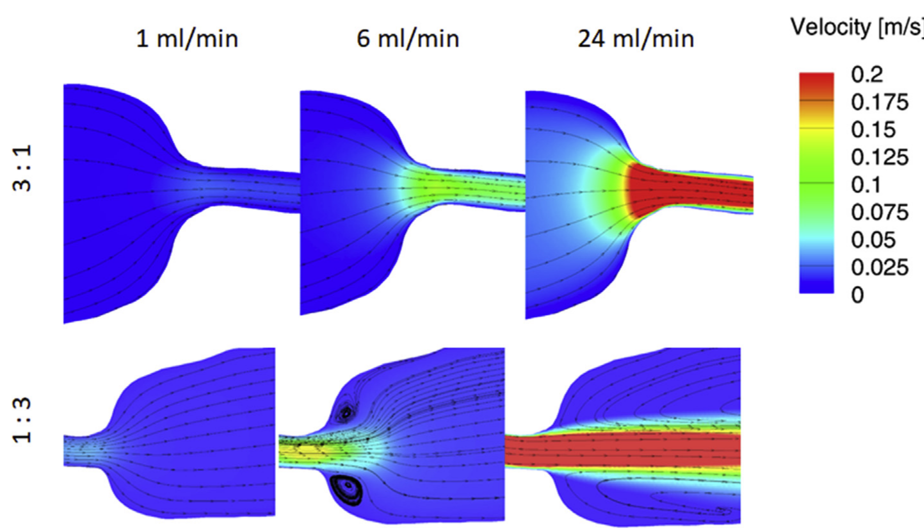

Fig. 6. Flow simulations of the ETE Anastomoses.

1–24 ml/min, which is most likely dependent on the different sizes of the free flaps. This theory is supported by the fact that we measured the largest mean flow rate of 8.3 (±8.1) ml/min in ALT flaps after anastomosis. Typically, these flaps have a high average volume.

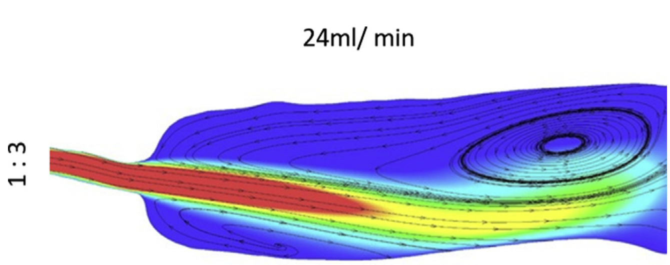

Fig. 7. Detailed figure of 1:3 ETE Anastomosis with 24 l/min.

The mean flow rate in radial forearm flaps, which have a substantially smaller volume, was only 3.5 (±2.2) ml/min after anastomosis. Regarding literature, there is only limited information about the venous flow rate in free flaps like the radial forearm flap or the ALT flap, especially for the head and neck region. Ichinose et al. compared the venous flow rate of the single cutaneous and the single deep vein before anastomosis in radial forearm flaps (Ichinose et al., 2003). They found a mean flow rate of 24.2 ml/min for the deep vein and 16.05 ml/min for the cutaneous vein, which is higher than our own cases with radial forearm flaps before the anastomosis (5.2 ml/min). These differences could be explained by the varying flap sizes. To our knowledge, there is no information about the venous flow rate in ALT or fibula flaps in the literature yet.

For the second aim of simulating the flow through the different designs of anastomoses, it was necessary to create a realistic model of the different types of anastomoses. The injection of light-body dental impression material inside the fresh porcine veins gave us the opportunity to gain stable vessel anastomosis. The depiction of the veins showed that the idea of two perfect pipes simulating an anastomosis can be considered as an oversimplification. Especially the sutures seem to have an impact on the inner geometry. Using a subsequent micro-CT-scan we were able to create resilient 3D models. According to the law of continuity, for a constant inflow, a decrease in vessel diameter leads to increased velocities. Therefore, it is not surprising that we found the highest velocity in the 1:3 or the 3:1 ETE anastomosis. Non-physiological vessel geometries (rapid diameter change) can cause recirculating flow patterns, which might lead to thrombus formation or complete occlusion of the vessel (Smith et al., 1972; Stein et al., 1974). Our simulations showed recirculation areas in special cases. Recirculation occurred in the ETS models with an angle of 60° and 90° at low blood flow in the flap vein. The recirculation areas were most probably caused by an inflow from the jugular vein, which was considerably larger than the inflow from free flap vein. Therefore, a low venous pressure inside the vein of the free flap will result in the mentioned volume backflow, which presents a risk factor for thrombosis or complete occlusion.

In the ETE cases, only the 1:3 ETE anastomosis showed conspicuous flow patterns. Areas of recirculation occurred in the simulation with medium or high flow and these areas were growing linear with a higher fluid flow rate. Accordingly, 24 ml/min of inflow led to the largest recirculation areas. In these situations, with high-caliber discrepancies and high flow rates in ETE anastomosis, recirculating blood flow could cause thrombosis and flap failure. A recent meta-analysis in 2017, including 34 articles with 1459 ETS venous anastomoses and 6133 ETE venous anastomoses, showed no significant differences in risk ratio between ETE and ETS anastomoses (Ahmadi et al., 2017). However, there is still discussion about this topic and sometimes it seems that the individual preferences play a matter in choosing the type of anastomosis. With the data collected in our study, it seems reasonable that the technique of venous anastomosis should be an individual decision depending on the specific intraoperative venous blood flow. If both techniques (ETE and ETS) are technically possible, we recommend the following: ETS anastomoses should be favored in cases with high caliber differences or with a high venous outflow. ETE anastomoses should be chosen in conditions with a low venous outflow, or at least any 90° ETS should be avoided in this case.

A lot of parameters, still not totally understood, seem to play a role in venous blood flow after flap anastomosis. Interestingly in our own study, only the cases of ALT flaps showed significant higher venous flow rates after the finished anastomosis than before the anastomosis. In radial forearm and fibula flaps, there were no significant changes in venous flow rates after completed anastomosis. Hansono et al. described the velocimetry in 81 free flaps before and after the anastomosis with Doppler ultrasonography (Hanasono et al., 2010). Although it was a measurement of the artery, this research group showed a significant rise in velocity after the finished anastomosis. The main reason for this phenomenon seems to be the denervation of the sympathetic nerves after flap raising, which is already described by Ichinose et al., in 2004 (Ichinose et al., 2004). In the venous system, there is no sympathetic innervation. We, therefore, hypothesized that the main reason for the varying venous blood outlet before and after anastomosis may be caused by the difference in size, the varying peripheral drainage and the individual blood requirement of the free flaps.

5. Conclusions

There are important differences in the fluid flow of ETE and ETS venous anastomosis. As areas of recirculation in ETE anastomoses with high caliber discrepancies occurred especially in cases with a larger diameter behind the anastomosis, we would suggest avoiding ETE anastomosis in these cases. Furthermore, our results suggest avoiding ETS anastomoses with an approximate angle of 90° in free flaps in conditions with a small venous volume outlet. To prove a clinical relevance of these simulations, further prospective clinical investigations are necessary. Nevertheless, our results could help surgeons in their decision-making process in cases with different possibilities of venous anastomosis.

Disclosures

The authors have no commercial associations or financial disclosures that might pose or create a conflict of interest with information presented in this article.

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