

# Development and Innovation of Modern Microvascular Anastomoses

Mofei Wang<sup>1</sup>, Hongbo Guo<sup>2</sup>, Guoxin Zhang<sup>2</sup>, Peng Ruan<sup>2</sup>, Kangkang Zhi<sup>2\*</sup>

<sup>1</sup>School of Health Science and Engineering, University of Shanghai for Science and Technology, Shanghai, China

<sup>2</sup>Department of Vascular and Endovascular Surgery, Changzheng Hospital, Naval Medical University, Shanghai, China

Email: \*kangkang\_zhi@163.com

**How to cite this paper:** Wang, M.F., Guo, H.B., Zhang, G.X., Ruan, P. and Zhi, K.K. (2024) Development and Innovation of Modern Microvascular Anastomoses. *Journal of Biosciences and Medicines*, 12, 105-118. <https://doi.org/10.4236/jbm.2024.1210011>

**Received:** September 13, 2024

**Accepted:** October 12, 2024

**Published:** October 15, 2024

Copyright © 2024 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

High-quality microvascular anastomosis is the foundation of successful microsurgery and one of the most important basic skills for microsurgeons. The traditional manual suture is recognized as the “gold standard” for microvascular anastomosis, but it still has problems such as long operation time and easy to cause vascular damage. In order to improve the success rate of microvascular anastomosis, reduce surgical complications and make the prognosis of patients better. In order to improve the success rate of microvascular anastomosis and reduce the surgical complications, scholars at home and abroad have developed some new vascular anastomosis techniques that are simple, fast and minimally invasive while improving the traditional surgical suturing methods. In this paper, we review the microvascular anastomosis, and its application research in two methods of traditional hand suture and non-suture anastomosis, in order to promote the application development of microvascular anastomosis.

## Keywords

Microvasculature, Couplers, Anastomosis, Microvascular Surgery

## 1. Introduction

With the rapid development of microsurgical techniques, clinical practice has evolved from simple finger (limb) transplantation to complex tissue reconstruction, achieving a comprehensive unity of function and aesthetics. In clinical practice, microvessels are defined as blood vessels with diameters usually less than 100 micrometers, including microarteries, microveins, and capillaries, and are the thinnest-walled vessels. Because of their extremely small vessel diameters, microvascular anastomoses remain one of the most challenging and critical

components of a successful anastomosis technique. French physicians first performed a microvascular anastomosis using sutures in 1920. In the United States, the first generation of microsurgical instruments was developed in 1960, which successfully hand anastomosed tiny blood vessels of 1.6 mm in diameter [1]. With the development of technology, microvascular anastomotic coupling devices (MACD) have already been an established technique for venous anastomosis. However, the application of arterial MACD is controversial. The overall percentage of first-time arterial MACD procedures without perioperative complications, revision or thrombosis was 88.9% (569/640) in Adam *et al.* [2]. The Grading of Recommendations, Assessment, Development and Evaluation (GRADE) quality analysis showed low quality and significant heterogeneity of the methodology. The use of arterial MACDs is a safe and effective alternative to manual suture anastomosis, and recent literature has shown excellent results. This has certainly taken the development of microvascular anastomotic devices a big step forward.

Although microvascular anastomosis techniques are constantly undergoing innovation. However, at present, in clinical microsurgery operation, the anastomosis of microvessels still mainly relies on manual suture technology. This process is not only complex, but also has a high technical threshold, which puts strict requirements on the surgeon's level of suturing, which makes it necessary to have extremely fine operation and high hand-eye coordination in the suturing process. The surgeon must accurately master the strength, angle, and spacing of the sutures to ensure the effective docking of blood vessels and smooth blood flow. The complexity and precision of manual suturing make this technique still dependent on the surgeon's experience and skill, which somewhat increases the difficulty and decreases the efficiency of microsurgical vascular anastomosis.

To this end, we will highlight the research advances in microvascular anastomosis from four perspectives: traditional microvascular suturing, microvascular mechanical anastomosis, vascular adhesives, and modified microvascular suturing techniques, as well as providing an outlook for the future of this field.

## **2. Traditional Microvascular Suturing Technique and Method**

The key technique in microsurgery is microvascular anastomosis, and microvascular suture anastomosis is still the gold standard in microvascular surgery [3]. Microvascular anastomosis has been developed for more than 60 years, and the most widely used technique in clinical practice is the standardised microvascular anastomosis technique, which includes the following four requirements: 1) Avoiding luminal narrowing after anastomosis; 2) The endothelium on both sides of the dissection should be tightly connected; 3) Ensuring that the lumen of the blood vessel is smooth; 4) Minimising the direct contact between the suture material and the blood [4]. Currently, the commonly used traditional microvascular suture methods include interrupted suture, continuous suture and mattress suture.

## 2.1. Sutureless versus Interrupted Sutures

The interrupted suture is the first used and most classic method, with the advantage of a low learning curve, applicability to arteriovenous and lymphatic anastomoses, and a high patency rate. However, the interrupted suture method requires repeating the same manoeuvre 4 to 6 times, and multiple knot tying results in a longer procedure time. In order to optimise the procedure time and improve efficiency, clinical researchers have proposed the continuous suture method, which not only reduces the procedure time, but also has a similar patency rate as the interrupted suture method.

Sertg *et al.* [5] compared interrupted versus continuous suturing with conventional knot tying and found that continuous suturing could reduce the operative time by 50%. However, there are potential disadvantages of continuous suturing: 1) The anastomotic site may form a narrowing ring, resulting in anastomotic stenosis due to excessive suture contraction, which reduces distal blood flow; 2) This technique leaves more suture material around the anastomosis, which increases the risk of the vessel wall coming into contact with the suture material, which may cause inflammation and even increase the risk of thrombosis. When anastomosing large-calibre vessels, both interrupted and continuous suture methods require an increased number of sutures, which inevitably prolongs the duration of the procedure and leads to an increase in tissue ischemia and hypoxia. Multiple needle insertions and removals can damage the vessel wall and intima, increasing the risk of thrombosis, and asymmetric needle insertion can lead to anastomotic blood leakage and lumen narrowing. In microvascular anastomosis, the interrupted suture method is significantly more difficult and requires more microsurgical skills from the surgeon, whereas the continuous suture method is not suitable because of its more obvious disadvantages.

## 2.2. Maintaining the Integrity of the Specifications

According to the results of a double-blind randomised study conducted by Sadick, it was found that small diameter and microvascular decubitus sutures enhance the quality of the anastomosis, and that modified decubitus sutures produced less hypertrophic scar/scarring formation (2% vs 16%), less spread of wound scarring (6% vs 24%), and a higher level of patient satisfaction with their postoperative recovery (96%). However, occasional residual skin surface sutures can produce abrasion, suture breakage, local tissue necrosis, infection and reactive fibrosis at exposed suture sites [6]-[9]. When comparing simple sutures with mattress sutures, it was found that mattress sutures result in varying degrees of narrowing of the internal diameter of blood vessels, which affects blood perfusion to the distal tissues. Inadequate tissue blood perfusion may lead to infection and necrosis and liquefaction of the grafted (re)implanted tissue in the short term [10]-[12]. Therefore, the disadvantages of the decubitus suture method are also obvious, as it tends to lead to luminal narrowing and thus more serious complications due to pulling the vessel wall over a longer distance.

### 2.3. Innovative Suturing Technique

Innovative suturing techniques have also advanced microsurgery while promoting advances in microvascular anastomosis. The techniques of “continuous suture” and “posterior wall priority suture” can effectively shorten the operation time, reduce the number of sutures, and complete the anastomosis in deep tissues. The “parachute” technique proposed by Agko M *et al.* [13] improves knotting and simplifies suturing. Cigna E *et al.* [14] proposed the “PCA (Percutaneous Transluminal Coronary Angioplasty)” technique for microvascular suturing, which was compared with the traditional interrupted suture method, and proved that the “PCA” technique not only saved time, but also was safe and reliable. Compared with the traditional interrupted suture method, the “PCA” technique not only saves surgical time, but also is safe and reliable. In addition, Volovici V *et al.* [15] proposed the “double-needle flap technique” for end-to-side anastomoses, which reduces the operating time and improves the efficiency of the suture, as well as ensures the flap of the vessel wall. Kuo S C *et al.* [16] further studied the microvascular anastomosis technique and proposed the “multiple U technique”, which combines continuous horizontal mattress suture and interrupted knotting, leaving multiple “U” shaped sutures on both sides of the vessel, and then interrupted knotting with the sutures of the next anastomosis respectively. This technique combines continuous horizontal mattress suturing and interrupted knotting, leaving multiple “U” shaped sutures on both sides of the vessel, which are then interrupted and tied to the next anastomotic suture, ensuring that the anastomosis is flared and the lining is in full contact, and is suitable for both arteries and veins.

Although these innovative suturing techniques have achieved satisfactory results in animal experiments or clinical trials, they are often difficult to implement in microvascular anastomosis of small calibre due to the emphasis on fine manipulation of their suturing techniques and their close relationship with blood vessels. Because of the constraints of small calibre and thin wall of microvessels and limited surgical space, these innovative suturing techniques are prone to damage the blood vessels easily, which may lead to the failure of vascular anastomosis, and therefore microvascular anastomosis remains one of the urgent problems to be solved in microsurgery.

### 3. Microvascular Mechanical Anastomosis Method

The technical threshold of microsurgery remains high as manual suturing of blood vessels is highly dependent on the experience and skill of the operator. On this basis, surgeons can only achieve higher anastomotic skills by training in segments with synthetic materials, isolated tissues and in animal experiments, and by accumulating experience over a long period of clinical practice. In order to reduce the difficulty of microvascular anastomosis and improve the quality of anastomosis, people have been developing and improving microvascular anastomoses. Currently, the commonly used microvascular anastomoses in clinical practice include magnetic tubes, anastomotic clips, and ring anastomoses. Due to obvious

disadvantages, the internal fixation needle method and the trocar method have been abandoned and are rarely seen in the literature.

### 3.1. Magnetic Tube

Magnetic catheterisation is a new microvascular anastomosis produced by bonding broken vessels together by means of a pair of specially designed magnetic rings. German scholars Klima U *et al.* [17] applied magnetic catheters in 32 cases of coronary artery bypass grafting and obtained a 100% patency rate. However, in China, there has not been any clinical study on the application of magnetic catheters for microvascular anastomosis. Previous studies have found that traditional magnetic materials have weak magnetic energy, large size and poor biocompatibility. However, Shi Y *et al.* [18] achieved permanent implantation by cladding a layer of titanium on the surface of NdFeB, which not only improved the magnetic force but also reduced the size. Xue F *et al.* [19] experimented with splenorenal bypass transplantation in dogs with equally satisfactory results.

### 3.2. Anastomosis Clip

Vessel closure system (VCS) is a new method proposed by Kirsch WM *et al.* [20] in 1992, the basic principle of which is to achieve smooth anastomosis of vessels without penetrating the tube wall by mechanically tightening the ectopic vessel breaks together [21]. The clamping force of VCS is based on elasticity, and a snap structure is also used; the material is mainly nickel-titanium alloy, and adsorbent substances such as polytetrafluoroethylene can also be used. However, VCS has three major obvious defects: 1) The surgical requirements for vascular ectasia and alignment at the severed port are high, and the surgical operation is cumbersome and the auxiliary device is complicated, which is not easy to be applied repeatedly; 2) The clamping force of VCS is difficult to be controlled, which may cause anastomotic leakage in the light case, or rupture of anastomosis and stenosis of the anastomosis in the heavy case; 3) The non-absorbable material of VCS will lead to loss of growth and diastolic ability of blood vessels in the area, so it is not suitable for the use of VCS.

### 3.3. Needle-Ring Anastomosis

The needle-ring anastomosis is one of the most commonly used and well-established microvascular anastomoses, and its basic principle is to form a ring of fine holes around the anastomotic rings. During the procedure, the severed vessel is suspended from the two anastomotic rings with an external flap and closed. This method has been clinically applied for many years and tested on animals, and has the following advantages: 1) Easy to operate without auxiliary tools; 2) Fast and can be operated on certain blood vessels under the human eye; and 3) Higher patency rate than the hand-stitching method. However, needle-ring fixation is not suitable for patients with atherosclerosis. Zhang Qiong used poly (lactic acid) and poly (caprolactone) to prepare biodegradable needle-ring microvascular anastomosis,

whose needle and ring were made of PLA, and the hot water at 50°C could be contracted and wrapped to enhance the strength of the needle-ring system. It was confirmed by animal tests that this method could shorten the time needed for suturing and there was no statistical significance between the two compared with manual suturing.

## 4. Vascular Adhesive Method

Adhesion is a method of regenerating blood vessels by gluing broken vessels together. It has the advantages of being less invasive, easy to use, and faster anastomosis, and is suitable for all types of microvascular anastomosis. The commonly used bioadhesives are fibrin glue, cyanoacrylate glue, BioGlue bioprotein glue, and a new tissue glue [22].

### 4.1. Fibrin Glue

It is a collagen gel with fibrinogen as the main component which is a final step similar to the natural clotting process. This technology has the ability to promote cell growth, is non-toxic, bioabsorbable, biocompatible, and can control coagulation and degradation time. Sacak *et al.* [23] found that combining biogel with venous cuffs significantly shortened anastomotic time, reduced bleeding, and did not have a significant effect on patency in a study on rats. However, due to its low mechanical strength, easy to form antibodies, cause coagulation dysfunction, prone to thrombosis, and prone to vascular embolism, there is no study on the application of fibrin gel alone as a microvascular anastomosis [24].

### 4.2. Cyanoacrylate Adhesives

Cyanoacrylate gel can quickly react with alkaline media such as water, blood and human tissue, so that it quickly adheres to the surface of the target material, and then through exothermic polymerisation, a film is formed at the break, which ultimately achieves the purpose of anastomosis. Currently, cyanoacrylate gel has been widely used for wound closure, wound coverage and prevention of wound infection, and is expected to replace suture anastomosis. The effectiveness of this method has been confirmed in many studies [25]-[27]. However, its application in deep tissues is still in the preliminary stage of research due to its debated tissue toxicity. In addition, the low tensile strength of this adhesive may cause side effects such as asthma, deep burns and tissue necrosis [28].

### 4.3. BioGlue Bio-Protein Gel

BioGlue Bio-Protein Gel is made of 45% BSA + 10% glutaraldehyde, which is covalently crosslinked to BSA (Bulky Segregant Analysis) by glutaraldehyde (Glutaraldehyde) to rapidly generate hydrogel and form a mechanical seal at the wound. Its main features are: 1) Strong adhesion, good sealing, can improve the tensile and shear strength of the product; 2) Room temperature storage, easy to use; 3) Good biodegradability. The U.S. FDA (Food and Drug Administration)

approved BioGlue BioProtein Gel in 2001 for use as an adjunctive therapy for haemostasis after open surgery on large vessels. The limitations of this technique are 1) it needs to be performed in a blood-free zone and the blood in the target zone needs to be drained first; and 2) slow absorption, which can cause local inflammation associated with tunica fibrosis, stenosis, and thrombosis [29]-[31]. There is now another breakthrough in BioGlue's research. Yu K [32] has invented a bioadhesive material inspired by spider webs and barnacles. It's a moisture-resistant adhesive material that stops bleeding and promotes repair and healing of damaged tissues and organs. And it is very easy to use compared to its competitors, this nature-inspired adhesive holds promise for wound healing and bleeding control.

#### 4.4. Emerging Tissue Adhesive

An ideal adhesive must meet the following conditions: 1) Be easy to handle and can be used on-site; 2) Have good mechanical elasticity and be able to adapt to a variety of different anastomotic modalities; 3) Have good biocompatibility; 4) Have suitable mechanical and physical properties, such as compressive, tensile, and shear resistance; 5) Have the ability to adhere to moist tissues or organs with high strength [33]. However, there is still a big gap between the bone glue used at present and the international standard, and it is necessary to study the existing bone glue. For example, conventional gelatin is used as raw material, and its hydrophobicity is improved by introducing dibutyldiimide, tartaric acid, polyethylene glycol, sodium alginate, etc., which enhances the gluing ability and bonding strength. Biomimetic glues are inspired by animals such as slugs, mussels, geckos, octopuses, etc., and can work under wet conditions [34]. In addition, *Bacillus subtilis* (*Bacillus subtilis*) peritoneum is a carrier for self-regeneration and environmental response [35]. However, the novel sealing materials are still in the experimental research stage, and their adhesive properties and potential clinical application risks are unknown.

### 5. Improved Microvascular Suturing Technique and Method

In clinical practice, traditional microvascular suturing techniques and methods often have difficulty in solving difficult problems such as asymmetric and deep microvascular anastomosis. In order to improve the quality of microvascular anastomosis, researchers have proposed a variety of improved suturing techniques and methods for different application scenarios.

#### 5.1. Asymmetric Calibre Anastomosis

The calibre of the vessels varies considerably from proximal to distal limb, especially at the branches, e.g. the diameter of the apical arteries in adults is 0.1 - 0.2 mm, whereas the diameter of the proximal innominate arteries varies to 0.3 - 0.5 mm. Surgeons need to use special methods of anastomosis for such vessel breaks with significant variations in calibre. Sleeve sutures (or cuff sutures) are used to suture small-calibre vessels into large-calibre vessels and have a high rate of anastomotic

patency. Studies by Ensinger SM *et al.* [36], Rowinska Z *et al.* [37] have shown that the sleeve suture is an alternative technique to end-to-end anastomosis for vessels with diameters of less than 1 mm and has been successfully used in a rat model. Zou YQ *et al.* [38] applied end-to-end anastomosis, cuff suture and cuff suture techniques to mouse models of grafted vessels, respectively, and found that the cuff suture technique not only significantly shortened the time for anastomosis of microvessels, but also had certain advantages in terms of bleeding and patency rate. However, this method requires vessel length and calibre, and is not applicable to microcalibre vessels; sufficient vessel length is needed for the snapping of the broken ends, and the calibre of the proximal vessel needs to be smaller than or equal to that of the distal end in order to be operated. In addition, this method may theoretically lead to anastomotic stenosis.

Another approach to asymmetric microvascular anastomosis is to expand the calibre by side-cutting small vessels to facilitate the anastomosis. This method is called “fish-mouth suture”, which is suitable for cases where the difference in calibre between the two ends is not more than half. Chung SR *et al.* [39] further proposed a four-cornered fish-mouth suture technique, and compared it with the traditional interrupted suture method through animal experiments, and found that the four-cornered fish-mouth suture technique not only reduced the number of sutures, but also shortened the operation time and reduced vascular complications. number of times, shorten the operation time, and also reduce the vascular complications. For large-calibre vessel dissection, the calibre can be reduced by oblique incision for anastomotic purposes. Although these methods are easy to operate and the anastomosis is fast, the secondary injury to the vessel may cause anastomotic thrombus and anastomotic leakage, so they are not suitable for the case where both severed ends are small-calibre vessels. Bali Z U *et al.* [40] successfully completed 12 free tissue grafting surgeries by obliquely placing the vascular clips to make the large-calibre vessels smaller, and the results showed that all the flaps successfully survived.

## 5.2. Shaped Microvascular Anastomosis

Based on the traditional method of microvascular anastomosis, the trapezoidal bisection method proposed by Feng Yagao and others [41] was modified, which can effectively reduce the loss of the inner and outer vessel membranes. The specific method is to cut off a small isosceles triangle at the 0° and 180° positions of the severed end of the vessel, so that the severed end is in the shape of a symmetrical trapezoid, which is more convenient for suturing after distinguishing the vessel level. Animal experiments and clinical trials verified the feasibility of this method. Li Tao *et al.* [42] studied the “T-shaped” microvascular anastomosis formed by the main stem of the peroneal artery and its perforating branches, and the results showed that the flaps of nine patients with limb defective wounds repaired by this method were all viable after the operation, and the therapeutic effect was satisfactory. The “sliced-pants” technique, proposed by Nicolaides M *et al.*

[43], allows suturing to larger recipient vessels by incising the sidewalls of the main vessel and the branch vessels so that the two luminal diameters form a uniform lumen. These methods are more in line with the principle of personalised treatment by altering the shape of the vascular cross-section to suit a particular situation or to achieve a specific purpose. While expanding the calibre of microvascular anastomosis, they also place higher demands on vascular trimming techniques, requiring the operator to have extensive experience in microvascular anastomosis for successful completion of the procedure. In addition, increasing the number of microvascular anastomotic needles also increases the risk of thrombosis, which makes it difficult to be widely used in clinical practice.

### 5.3. Laser-Assisted Vascular Anastomosis

Laser-assisted vascular anastomosis (LAVA) requires the selection of appropriate laser parameters (wavelength, spot size, energy density, etc.) based on the size of the vessel to be anastomosed and matched to the welding material and time. Different types of lasers have different wavelengths, *i.e.*, variations in depth of penetration [44]. The most common lasers currently available are carbon monoxide lasers, Nd: YAG, semiconductor lasers and argon lasers. Weld material (Solder), also called enhancer, is an excipient that absorbs laser light at specific wavelengths and has the ability to mitigate vascular damage and enhance anastomotic stability. From the initial liquid form (e.g., blood), later semi-solid materials such as fibrin, methylene blue-based proteins, and protein/dye mixtures [45]. In recent years, the use of solid brazing materials based on poly (lactide-co-glycolide) PLGA (poly (lactide-co-glycolide) PLGA) and polyethylene oxide (polyethylene oxide, PEO) can effectively reduce the difficulty of the surgery and postoperative complications. Currently, there are few clinical applications of this technique, and in-depth studies on laser parameter setting, brazing material selection, and biosafety are yet to be carried out. Leclé *et al.* [46] achieved microvascular anastomoses of less than 15 mm using semiconductor laser-assisted manual suturing in 11 hand surgery patients.

### 5.4. Tissue-Engineered Blood Vessels

When severe trauma is repaired, heart bypasses are performed, or there is a lack of adequate blood vessels, a portion of the blood vessel is often extracted from the patient, which can increase the patient's pain. Tissue-engineered blood vessels (TEBVs) are a new type of vascular material. From glass and metal tubes at the beginning of the twentieth century to today's fluoropolymers used to repair large arteries in the human body, their diameters are usually more than 1 cm. Thinner tube diameters can lead to thrombosis and endothelial proliferation. Although much progress has been made in engineering vascular grafts for large and small diameter arterial repair or bypass grafts, extending these results to the microsurgical size scale has been challenging.

Currently, there has been considerable progress in the study of small-calibre

vascular microsurgery. Li *et al.* [47] preimplanted vascular endothelial cells into collagen tubes to make 1 mm diameter TEBVs, which were implanted into femoral arteries and femoral veins of mice. The endothelialised dense collagen tubes could remain patent for up to 7 days after microvascular microsurgery without the addition of any anticoagulant drugs. Kimicata *et al.* [48] prepared biomixed blood vessels with a diameter of 1 mm by combining decellularised pericardial extracellular matrix with polypropylene fumarate. Jirofti *et al.* [49] used poly (terephthalic acid) tetramethylene terephthalate (PET), polyurethane (PU) and polycaprolactone (PCL) composite to prepare TEBVs with good circumferential stress, fracture pressure and structural flexibility.

## 6. Summary and Outlook

In the development of microvascular anastomosis, the traditional microvascular suture technique is still the foundation, which mainly includes interrupted and continuous suture, mattress suture and other methods. These traditional methods are widely used in clinical practice due to their reliability and universal applicability. However, as microsurgical techniques continue to advance, innovative suturing techniques are emerging. These new techniques include, but are not limited to, the use of biomaterials and mechanically assisted anastomoses, which provide more options for microsurgery. These innovative approaches have not only demonstrated the potential to improve the quality and efficiency of suturing, but have also contributed to the development and optimisation of microvascular anastomosis by reducing the difficulty of the operation, increasing the efficiency of the procedure and reducing the incidence of postoperative complications.

Among the microvascular mechanical anastomosis methods, the magnetic tube method, anastomotic clip method, and needle loop method each have their own characteristics, which have significantly improved the anastomosis efficiency and effectiveness. In addition, the vascular adhesive method is constantly developing, and adhesives such as fibrin glue, cyanoacrylate glue, and BioGlue bioprotein glue provide reliable choices for vascular anastomosis, and the emerging tissue adhesives have injected new vitality into this field. In terms of improved microvascular suturing techniques, new techniques such as asymmetric calibre anastomosis, shaped microvascular anastomosis and laser microvascular anastomosis are being gradually promoted and applied. Meanwhile, the research on tissue-engineered blood vessels has also made remarkable progress, providing more possibilities for the future development of microvascular anastomosis.

In summary, although microvascular anastomosis technology is developing at a high speed, it is still at a very early stage, and there is still a long way to go before it enters the clinic and becomes commercialised. It is believed that with the continuous maturation of microscopic technology and the deepening of related research, the difficulties hindering the application of microvascular anastomosis will be solved eventually. By then, microvascular anastomosis technology will play an important role in microsurgery.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

- [1] Savlania, A. (2017) Alexis Carrel: Father of Vascular Anastomosis and Organ Transplantation. *Indian Journal of Vascular and Endovascular Surgery*, **4**, 115-117. [https://doi.org/10.4103/ijves.ijves\\_30\\_17](https://doi.org/10.4103/ijves.ijves_30_17)
- [2] Adam, D., Broderick, D., Kyzas, P. and Vassiliou, L. (2021) Microvascular Anastomotic Coupler Devices versus Hand-Sewn Technique for Arterial Anastomosis: A Systematic Review. *British Journal of Oral and Maxillofacial Surgery*, **59**, 524-533. <https://doi.org/10.1016/j.bjoms.2020.10.286>
- [3] Bauer, F., Fichter, A.M., Loeffelbein, D.J., Wolff, K., Schütz, K. and Mücke, T. (2015) Microvascular Anastomosis Using Modified Micro-Stents: A Pilot *in Vivo* Study. *Journal of Cranio-Maxillofacial Surgery*, **43**, 204-207. <https://doi.org/10.1016/j.jcms.2014.11.005>
- [4] Moritz, W.R., Raman, S., Pessin, S., Martin, C., Li, X., Westman, A., *et al.* (2022) The History and Innovations of Blood Vessel Anastomosis. *Bioengineering*, **9**, Article 75. <https://doi.org/10.3390/bioengineering9020075>
- [5] Sert, G., Aksoyler, D., Kara, M., Bolletta, A., Losco, L., Cam, S.B., *et al.* (2022) Comparison of Total Anastomosis Time between Four Different Combinations of Suturing and Knot Tying Techniques in Microsurgical Anastomosis. *Journal of Plastic Surgery and Hand Surgery*, **57**, 240-246. <https://doi.org/10.1080/2000656x.2022.2052083>
- [6] Sadick, N.S., D'Amelio, D.L. and Weinstein, C. (1994) The Modified Buried Vertical Mattress Suture. *The Journal of Dermatologic Surgery and Oncology*, **20**, 735-739. <https://doi.org/10.1111/j.1524-4725.1994.tb03195.x>
- [7] Justan, I. (2010) New Type of Skin Suture-Fully Buried Running Mattress Suture. *Journal of Plastic, Reconstructive & Aesthetic Surgery*, **63**, e338-e339. <https://doi.org/10.1016/j.bjps.2009.06.041>
- [8] Hohenleutner, Nicole Egner, Silvia, U. (2000) Intradermal Buried Vertical Mattress Suture as Sole Skin Closure: Evaluation of 149 Cases. *Acta Dermato-Venereologica*, **80**, 344-347. <https://doi.org/10.1080/000155500459277>
- [9] Maher, I.A., Bingham, J. and Mellette, R. (2012) A Running Modification of the Percutaneous Buried Vertical Mattress. *Dermatologic Surgery*, **38**, 1560-1562. <https://doi.org/10.1111/j.1524-4725.2012.02493.x>
- [10] Thiem, D.G.E., Frick, R.W., Goetze, E., Gielisch, M., Al-Nawas, B. and Kämmerer, P.W. (2020) Hyperspectral Analysis for Perioperative Perfusion Monitoring—A Clinical Feasibility Study on Free and Pedicled Flaps. *Clinical Oral Investigations*, **25**, 933-945. <https://doi.org/10.1007/s00784-020-03382-6>
- [11] Kehrer, A., Lamby, P., Miranda, B.H., Prantl, L. and Dolderer, J.H. (2017) Flap Design and Perfusion Are Keys of Success: Axial Fasciocutaneous Posterior Thigh Flaps for Deep Small Pelvic Defect Reconstruction. *Clinical Hemorheology and Microcirculation*, **64**, 305-318. <https://doi.org/10.3233/ch-168105>
- [12] Garvey, P.B., Salavati, S., Feng, L. and Butler, C.E. (2011) Perfusion-Related Complications Are Similar for DIEP and Muscle-Sparing Free TRAM Flaps Harvested on Medial or Lateral Deep Inferior Epigastric Artery Branch Perforators for Breast Reconstruction. *Plastic and Reconstructive Surgery*, **128**, 581e-589e. <https://doi.org/10.1097/prs.0b013e318230c122>
- [13] Agko, M., Ciudad, P. and Chen, H. (2017) “Airborne” Suture Tying Technique:

- Simple Steps to Make It Easy. *Head & Neck*, **39**, 2558-2561.  
<https://doi.org/10.1002/hed.24923>
- [14] Cigna, E., Curinga, G., Bistoni, G., Spalvieri, C., Tortorelli, G. and Scuderi, N. (2008) Microsurgical Anastomosis with the 'PCA' Technique. *Journal of Plastic, Reconstructive & Aesthetic Surgery*, **61**, 762-766. <https://doi.org/10.1016/j.bjps.2008.04.003>
- [15] Volovici, V., Dammers, R. and Zamfirescu, D.G. (2016) The Double Stitch Everting Technique in End-to-Side Vascular Anastomoses. *Microsurgery*, **37**, 88-89.  
<https://doi.org/10.1002/micr.30021>
- [16] Kuo, S.C., Tsai, Y., Kuo, P., Huang, F., Lin, T. and Hsieh, C. (2022) The Multiple-U Technique: A Novel Microvascular Anastomosis Technique That Guarantees Everted Anastomosis Sites with Solid Intima-to-Intima Contact. *Plastic & Reconstructive Surgery*, **149**, 981e-984e. <https://doi.org/10.1097/prs.00000000000009025>
- [17] Klima, U., Falk, V., Maringka, M., Bargenda, S., Badack, S., Moritz, A., *et al.* (2003) Magnetic Vascular Coupling for Distal Anastomosis in Coronary Artery Bypass Grafting: A Multicenter Trial. *The Journal of Thoracic and Cardiovascular Surgery*, **126**, 1568-1574. [https://doi.org/10.1016/s0022-5223\(03\)01314-x](https://doi.org/10.1016/s0022-5223(03)01314-x)
- [18] Shi, Y., Jiang, A. and Zhang, Y. (2007) Novel Magnetic Rings for Rapid Large Vascular Reconstruction in Canine Liver Transplantation Model. *Chinese Journal of Reparative and Reconstructive Surgery*, **21**, 420-423.
- [19] Xue, F., Li, J., Lu, J., Zhu, H., Liu, W., Zhang, H., *et al.* (2016) Splenorenal Shunt via Magnetic Compression Technique: A Feasibility Study in Canine and Cadaver. *Minimally Invasive Therapy & Allied Technologies*, **25**, 329-336.  
<https://doi.org/10.1080/13645706.2016.1213750>
- [20] Kirsch, W.M., Zhu, Y.H., Hardesty, R.A., *et al.* (1992) A New Method for Microvascular Anastomosis: Report of Experimental and Clinical Research. *The American Surgeon*, **58**, 722-727.
- [21] Li, H., Gale, B., Shea, J., Sant, H., Terry, C.M. and Agarwal, J. (2017) Vascular Coupling System for End-To-End Anastomosis: An *in Vivo* Pilot Case Report. *Cardiovascular Engineering and Technology*, **8**, 91-95.  
<https://doi.org/10.1007/s13239-017-0294-1>
- [22] Annabi, N., Zhang, Y., Assmann, A., Sani, E.S., Cheng, G., Lassaletta, A.D., *et al.* (2017) Engineering a Highly Elastic Human Protein-Based Sealant for Surgical Applications. *Science Translational Medicine*, **9**, eaai7466.  
<https://doi.org/10.1126/scitranslmed.aai7466>
- [23] Sacak, B., Tosun, U., Egemen, O., Sakiz, D. and Ugurlu, K. (2014) Microvascular Anastomosis Using Fibrin Glue and Venous Cuff in Rat Carotid Artery. *Journal of Plastic Surgery and Hand Surgery*, **49**, 72-76.  
<https://doi.org/10.3109/2000656x.2013.800528>
- [24] Caers, J., Reekmans, A., Jochmans, K., *et al.* (2003) Factor V Inhibitor after Injection of Human Thrombin (Tissucol) into a Bleeding Peptic Ulcer. *Endoscopy*, **35**, 542-544.
- [25] Schwaiger, N., Wu, J., Wright, B., Morrissey, L., Harris, M. and Rohanzadeh, R. (2010) Bioweld® Tube and Surgical Glue for Experimental Sutureless Venous Microanastomosis. *British Journal of Surgery*, **97**, 1825-1830.  
<https://doi.org/10.1002/bjs.7257>
- [26] Chang, E.I., Galvez, M.G., Glotzbach, J.P., Hamou, C.D., El-ftesi, S., Rappleye, C.T., *et al.* (2011) Vascular Anastomosis Using Controlled Phase Transitions in Poloxamer Gels. *Nature Medicine*, **17**, 1147-1152. <https://doi.org/10.1038/nm.2424>
- [27] Zhao, Y., Lv, H., Lu, C., Chen, L., Lin, M., Zhang, M., *et al.* (2013) Evaluation of a

- Novel Thermosensitive Heparin-Poloxamer Hydrogel for Improving Vascular Anastomosis Quality and Safety in a Rabbit Model. *PLOS ONE*, **8**, e73178. <https://doi.org/10.1371/journal.pone.0073178>
- [28] Bao, Z., Gao, M., Sun, Y., Nian, R. and Xian, M. (2020) The Recent Progress of Tissue Adhesives in Design Strategies, Adhesive Mechanism and Applications. *Materials Science and Engineering: C*, **111**, Article ID: 110796. <https://doi.org/10.1016/j.msec.2020.110796>
- [29] LeMaire, S.A., Ochoa, L.N., Conklin, L.D., Schmittling, Z.C., Üндar, A., Clubb, F.J., *et al.* (2007) Nerve and Conduction Tissue Injury Caused by Contact with Bioglue. *Journal of Surgical Research*, **143**, 286-293. <https://doi.org/10.1016/j.jss.2006.10.014>
- [30] Gaberel, T., Borgey, F., Thibon, P., Lesteven, C., Lecoutour, X. and Emery, E. (2010) Surgical Site Infection Associated with the Use of Bovine Serum Albumine-Glutaraldehyde Surgical Adhesive (Bioglue®) in Cranial Surgery: A Case-Control Study. *Acta Neurochirurgica*, **153**, 156-163. <https://doi.org/10.1007/s00701-010-0830-3>
- [31] LeMaire, S.A., Schmittling, Z.C., Coselli, J.S., Üндar, A., Deady, B.A., Clubb, F.J., *et al.* (2002) Bioglue Surgical Adhesive Impairs Aortic Growth and Causes Anastomotic Strictures. *The Annals of Thoracic Surgery*, **73**, 1500-1506. [https://doi.org/10.1016/s0003-4975\(02\)03512-9](https://doi.org/10.1016/s0003-4975(02)03512-9)
- [32] Dolgin, E. (2023) Bioglue Breakthrough. *Nature*. <https://doi.org/10.1038/d41586-023-01661-2>
- [33] Pinkas, O., Goder, D., Noyvirt, R., Peleg, S., Kahlon, M. and Zilberman, M. (2017) Structuring of Composite Hydrogel Bioadhesives and Its Effect on Properties and Bonding Mechanism. *Acta Biomaterialia*, **51**, 125-137. <https://doi.org/10.1016/j.actbio.2017.01.047>
- [34] Baik, S., Kim, J., Lee, H.J., Lee, T.H. and Pang, C. (2018) Highly Adaptable and Bio-compatible Octopus-Like Adhesive Patches with Meniscus-Controlled Unfoldable 3D Microtips for Underwater Surface and Hairy Skin. *Advanced Science*, **5**, Article ID: 1800100. <https://doi.org/10.1002/advs.201800100>
- [35] Ma, A. (2018) Research Progress of Medical Composite Biological Bone Glue. *Chinese Journal of Chemistry and Adhesion*, **40**, 5.
- [36] Ensminger, S. (2000) Development of a Combined Cardiac and Aortic Transplant Model to Investigate the Development of Transplant Arteriosclerosis in the Mouse. *The Journal of Heart and Lung Transplantation*, **19**, 1039-1046. [https://doi.org/10.1016/s1053-2498\(00\)00195-9](https://doi.org/10.1016/s1053-2498(00)00195-9)
- [37] Rowinska, Z., Gorressen, S., Merx, M.W., Koepfel, T.A., Zerneck, A. and Liehn, E.A. (2017) Using the Sleeve Technique in a Mouse Model of Aortic Transplantation—An Instructional Video. *Journal of Visualized Experiments*, **128**, Article 54915. <https://doi.org/10.3791/54915>
- [38] Zou, Y., Liu, H., Cheng Zhou, and Wu, J. (2021) Sleeve Technique Is Superior to End-To-End Anastomosis and Cuff Technology in Mouse Model of Graft Vascular Disease. *Annals of Vascular Surgery*, **73**, 438-445. <https://doi.org/10.1016/j.avsg.2021.01.055>
- [39] Chung, S.R., Choudhury, M.M., Too, S.J.Y., Ong, C.B., Steele, T.W.J., McGrouther, D.A., *et al.* (2019) Microvascular Anastomosis with Fish-Mouth Suturing and Adhesive Sealants. *Journal of Plastic, Reconstructive & Aesthetic Surgery*, **72**, 137-171. <https://doi.org/10.1016/j.bjps.2018.10.031>
- [40] Bali, Z.U., Evrenos, M.K., Karatan, B., Kecici, Y. and Yoleri, L. (2019) An Effective Technique for Managing Vascular Diameter Discrepancies in Microsurgery: Tapering with a Hemoclip. *Journal of Plastic Surgery and Hand Surgery*, **54**, 19-23.

- <https://doi.org/10.1080/2000656x.2019.1657435>
- [41] Feng, Y., Fu, L., Yang, J., *et al.* (2002) Small Vascular Anastomosis with Two Trapezoid and Symmetrical Lobulated Flap. *Journal of Clinical Orthopaedics*, **5**, 30-32.
- [42] Li, T., Chen, Z., Cong, X., *et al.* (2014) Clinical Application of Peroneal Artery Perforator Flap Grafts with “T-Shaped” Vascular Anastomosis. *Chinese Journal of Microsurgery*, **37**, 486-488.
- [43] Nicolaidis, M. and Pafitanis, G. (2022) Overcoming Size Discrepancy in Microvascular Anastomosis: The ‘Sliced-Pants’ Technique. *The Annals of The Royal College of Surgeons of England*, **104**, 234-235. <https://doi.org/10.1308/rcsann.2021.0188>
- [44] Pabittei, D.R., Heger, M., van Tuijl, S., Simonet, M., de Boon, W., van der Wal, A.C., *et al.* (2015) *Ex Vivo* Proof-of-Concept of End-to-End Scaffold-Enhanced Laser-Assisted Vascular Anastomosis of Porcine Arteries. *Journal of Vascular Surgery*, **62**, 200-209. <https://doi.org/10.1016/j.jvs.2014.01.064>
- [45] Schönfeld, A., Constantinescu, M., Peters, K. and Frenz, M. (2018) Electrospinning of Highly Concentrated Albumin Patches by Using Auxiliary Polymers for Laser-Assisted Vascular Anastomosis. *Biomedical Materials*, **13**, Article ID: 055001. <https://doi.org/10.1088/1748-605x/aac332>
- [46] Leclère, F.M., Schoofs, M., Vogt, P., Casoli, V. and Mordon, S. (2015) 1950-nm Diode Laser-Assisted Microanastomoses (LAMA): An Innovative Surgical Tool for Hand Surgery Emergencies. *Lasers in Medical Science*, **30**, 1269-1273. <https://doi.org/10.1007/s10103-015-1711-z>
- [47] Li, X., Xu, J., Bartolák-Suki, E., *et al.* (2020) Evaluation of 1-Mmdiameter Endothelialized Dense Collagen Tubes in Vascular Microsurgery. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, **108**, 2441-2449.
- [48] Kimicata, M., Allbritton-King, J.D., Navarro, J., *et al.* (2020) Assessment of Decellularized Pericardial Extracellular Matrix (ECM) and Poly(Propylene Fumarate) (PPF) Biohybrid for Small-Diameter Vascular Graft Applications. *Acta Biomaterialia*, **110**, 68-81.
- [49] Jirofti, N., Mohebbi-Kalhari, D., Samimi, A., *et al.* (2020) Fabrication and Characterization of Novel Compliant Smalldiameter PET/PU/PCL Triad-Hybrid Vascular Graft. *Biomedical Materials*, **15**, Article ID: 055004.