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Research progress on vascular anastomosis technology

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Highlights

- Systematic classification of anastomosis techniques, including manual sutures, robotic assistance, biomedical adhesives, energy welding, and stapling devices.
- Critical analysis of biodegradable materials in addressing foreign body reactions and balancing degradation and mechanical performance.
- Future directions emphasizing intelligent material design, multimodal technology fusion, and specialized device development.

Abstract

Vascular anastomosis, as one of the core surgical techniques, directly determines clinical efficacy in trauma repair, organ transplantation, and vascular reconstruction. This paper systematically reviews the development and current research status of vascular anastomosis techniques such as traditional manual sutures, robotic-assisted technologies, biomedical adhesives, and energy welding. Traditional manual sutures, regarded as the gold standard of vascular anastomosis, have achieved ultra-precise anastomosis at the 0.1-mm level through advancements in microsurgical techniques, making them the most clinically prevalent method. However, they are limited by issues such as foreign body retention, high demands on surgeon, prolonged operative times, and high postoperative stenosis rates. Robotic-assisted systems offer enhanced precision in complex anatomical regions, achieving submillimeter accuracy. However, their widespread adoption is constrained by high costs, reliance on suturing, and steep learning curves. Biomedical adhesives and energy welding techniques significantly reduce operative time but are not yet clinically applicable due to insufficient anastomotic strength. Although the GEM Coupler stapling devices have been clinically applied, other stapling technologies remain limited in scope, with ongoing research in structural designs and biodegradable materials. Future advances in vascular anastomosis are expected to focus on three directions: material innovation, technological breakthroughs, and clinical translation.

Keywords: Vascular anastomosis, manual sutures, stapling devices, biodegradable materials

I Introduction

Vascular anastomosis, as a core technique in surgical practice, involves the precise reconnection of severed vessel ends to restore vascular continuity, ensuring unimpeded blood flow and maintaining normal physiological functions of tissues and organs. Based on vascular injury patterns, three primary anastomotic configurations are employed: end-to-end anastomosis, end-to-side anastomosis, and side-to-side anastomosis [1]. End-to-end anastomosis is suitable for transverse injuries requiring precise matching of luminal diameters and axial alignment; End-to-side anastomosis is commonly used in bypass grafting or for connecting vessels with significant diameter discrepancies; and Side-to-side anastomosis is applied in vas-

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cular shunting and dialysis access creation. These techniques are extensively utilized in trauma management, vascular pathology reconstruction, plastic surgery, and organ transplantation [2-5]. The continuous advancement of various surgical techniques and the increasing complexity of surgical procedures have put forward higher requirements for vascular anastomosis technology, demanding higher precision, efficiency and reduced complications.

Although traditional manual sutures are cost-effective and adaptable, they are prone to mechanical endothelial damage and are associated with high postoperative restenosis rates [6]. Notably, breakthroughs in super microsurgical techniques have enabled manual sutures to achieve 0.1-mm level precision in vascular anastomosis [7]. However, super microsurgical operations require extensive microsurgical expertise, with complex anatomical sites such as intracranial vessels requiring up to 30 minutes for anastomosis, significantly increasing the risk of ischemic complications [8].

In recent years, vascular anastomosis techniques have undergone a transformative shift from manual sutures toward minimally invasive and intelligent approaches. Robotic-assisted systems, leveraging multi-degree-of-freedom precise manipulation, achieve submillimeter-level anastomotic precision [9]. Non-suture techniques, such as laser welding, biomedical adhesives, and stapling devices, reduce operative time to 5-10 minutes [10-14]. Furthermore, the integration of novel biodegradable materials into stapling devices has significantly mitigated the risk of foreign body reaction [15].

In conclusion, vascular anastomosis, as a critical surgical technique, significantly enhances patients' quality of life and recovery rates by restoring or optimizing blood perfusion. Clinicians and researchers worldwide are continuously advancing research in anastomotic techniques, device design, and material science to improve the precision, safety, and procedural efficiency of vascular anastomosis, ultimately delivering superior therapeutic outcomes and rehabilitation. This review aims to systematically evaluate the advancements, limitations, and clinical applicability of both traditional and emerging vascular anastomosis techniques, providing evidence-based insights for future research directions.

II Review progress

Vascular anastomosis methods

Manual sutures

Manual sutures involve using sutures and surgical needles to approximate blood vessels. This technique remains the most clinically prevalent anastomotic method and is widely recognized as the gold standard for vascular anastomosis. The history of vascular surgery has been subject to debate, with no unified consensus. In 1889, Alexander Jassinowsky proposed the feasibility of vascular suturing and successfully performed an arterial anastomosis two years later [16]. In 1897, J.B. Murphy expanded upon Jassinowsky's work by introducing a novel framework for vascular anastomosis [17]. However, both pioneers erroneously concluded that endothelial disruption would inevitably trigger coagulation, hindering successful implementation. In 1902, French surgeon Alexis Carrel introduced a groundbreaking suturing method: placing three equidistant sutures at the vascular rupture site to stabilize the wound into a triangular configuration, followed by everting the vessel ends, precisely aligning them, and suturing with sterilized silk threads [18]. This approach ensured a smooth intraluminal surface and unobstructed blood flow. Carrel further established four ideal principles for vascular anastomosis: (1) Prevention of luminal stenosis at the anastomotic site; (2) Maintenance of intimal smoothness; (3) Tight intimal apposition between vascular ends; (4) Avoidance of direct contact between sutures and blood [19]. The advent of microsurgical manual sutures in 1960 marked the beginning of microvascular suturing techniques under microscopy. However, super-microsurgical operations demand exceptional microsurgical expertise, with complex anatomical sites such as intracranial vessels requiring 30 minutes for anastomosis [8]. Persistent challenges, including operator hand tremor and visual fatigue, substantially elevate the risks of ischemic complications.

Furthermore, the properties of suture materials critically influence vascular healing outcomes. Surgical sutures must exhibit optimal biocompatibility, sufficient tensile strength, and ease of knotting. Sutures are broadly classified into absorbable and non-absorbable categories. Absorbable sutures, such as polyglycolic acid

(PGA), polydioxanone (PDS), polyhydroxybutyrate (PHB), and polylactic acid (PLA), are rarely used in vascular anastomosis due to their prolonged retention within vessels, which poses a high infection risk [20]. In clinical vascular suturing, non-absorbable sutures are commonly employed. These sutures, made from non-degradable materials such as nylon, polyester, polytetrafluoroethylene (PTFE), and polypropylene, offer superior mechanical strength, with polypropylene being the most widely used in vascular surgery due to its excellent strength.

Manual sutures, despite their advantages of stable clinical efficacy, cost-effectiveness, and ease of implementation, are associated with significant limitations, including operator-dependent outcomes, prolonged operative times, and suture-induced foreign body retention. The latter can trigger inflammatory responses, platelet aggregation, endothelial dysfunction, and intimal hyperplasia, ultimately leading to anastomotic stenosis. To address these shortcomings, alternative vascular anastomosis techniques have been developed to mitigate the inherent limitations of manual sutures.

Robotic-assisted anastomosis

With the rapid advancement of automation control and computer vision technology, robotic systems have increasingly been integrated into medical practice. In 1985, robots were first applied in healthcare as positioning assistance devices during neurosurgical procedures [21]. Subsequently, robotic technology has been applied across diverse surgical disciplines, including neurosurgery, minimally invasive surgery, and microsurgery. Robotic-assisted vascular anastomosis emerged as an extension of medical robotics development. In this approach, the surgeon, seated at a console, manipulates robotic arms and instruments via control interfaces, such as trackballs and control wheels. This approach combines the benefits of minimally invasive approaches with robotic precision, enabling submillimeter-level accuracy in vascular anastomosis.

In 1995, Intuitive Surgical developed the prototype of the da Vinci Surgical System, named “Lenny”, which required fixation to the operating table and lacked interchangeable instruments [22]. In 2000, the da Vinci system received approval from the U.S. Food and Drug Administration (FDA) and began tis widespread application in general surgery. In 2002, Wisselink et al. first reported two successful cases of robotic-assisted laparoscopic aorto-femoral bypass procedures [23]. Subsequently, robotic surgical systems have evolved toward diversification and specialization: The da Vinci platform has undergone iterative upgrades, expanding to complex procedures such as single-port surgery; Emerging systems like Hugo of Medtronic and Versius of CMR utilize modular and lightweight designs to reduce costs; and domestic Chinese systems, including “Tianji” and “Tuomai”, have overcome technical barriers and entered clinical use. Furthermore, robotic-assisted vascular anastomosis has been validated in broader applications, such as renal transplantation and pancreaticoduodenectomy, demonstrating enhanced surgical efficacy and safety profiles [9, 24, 25].

Compared to traditional manual sutures, medical robotic systems offer distinct advantages: reduced operator fatigue, enhanced maneuverability, improved surgical precision, and the ability to perform anastomose in narrow surgical fields or with submillimeter diameters [26]. However, robotic-assisted vascular anastomosis presents several limitations: (1) Prolonged operative time, with no significant reduction compared to manual sutures; (2) Persistent reliance on sutures, inheriting suture-related complications; (3) High costs and maintenance demands. For instance, the da Vinci Surgical System is priced at up to $ 3.5 million, with disment and regular maintenance. This economic burden restricts effective surgeon training, potentially increasing procedural risks; (4) Immature haptic feedback technology. While current systems integrate force feedback, vibration sensing, and visual cues to simulate tactile perception, yet their force resolution and dynamic response rates remain inadequate for complex vascular anastomosis; (5) Technically demanding operations with a steep learning curve [27].

Biomedical adhesives

Biomedical adhesives refer to vascular anastomosis methods utilizing biocompatible adhesive materials, as shown in **Figure 1**. Based on their composition, they are classified into natural adhesives, semi-synthetic adhesives, and synthetic adhesives. Early biomedical adhesives

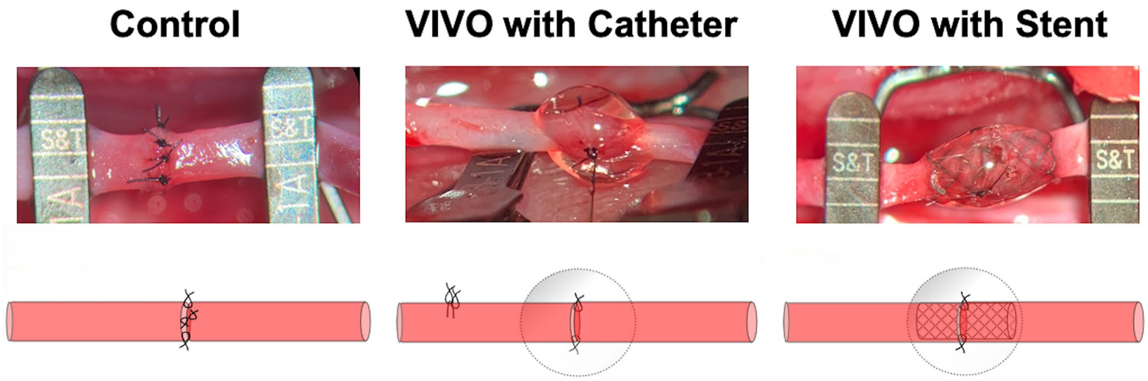

Figure 1. Biomedical adhesives: Sealants combined with sutures and stents [58].

were primarily natural derivatives, offering excellent biocompatibility and degradability but limited adhesive strength and durability, thus rarely applied in vascular anastomosis. In 1960, Nathan H. pioneered the use of synthetic adhesives for vascular repair [28]. Despite significant advancements in material formulations and delivery systems in recent decades, the core functionalities of these adhesives in vascular anastomosis remain consistent: (1) Hemostatic agents to promote wound healing; (2) Sealants, often combined with sutures or stents, to enhance anastomotic integrity and prevent postoperative leaks; (3) Standalone adhesives applied directly to vascular ends for sutureless anastomosis [29-31].

Biomedical adhesives offer several advantages, including minimal vascular wall trauma, procedural simplicity, rapid anastomosis, and adaptability to diverse vascular configurations. Representative tissue adhesives include fibrin glue, cyanoacrylate adhesives, and BioGlue biologic sealant. An ideal vascular adhesive should possess the following characteristics: (1) High mechanical strength to securely bond vascular ends and withstand hemodynamic forces; (2) Excellent biocompatibility, without inducing immune responses or thrombogenesis; (3) Controlled degradability to allow gradual absorption while minimizing long-term foreign body reactions; (4) Ease of preparation and application; (5) Non-interference with tissue function and mobility [10]. Despite their potential, biomedical adhesives face critical challenges in vascular applications, including insufficient long-term durability under cyclic mechanical stress, incomplete vascular wall compatibility leading to interfacial failure, and instability in dynamic hemodynamic environments. Consequently, researchers are actively developing novel materials and engineering strategies to enhance adhesive performance and safety. While various bioadhesives have demonstrated efficacy in preclinical studies, none have yet achieved successful clinical translation for vascular anastomosis.

Energy welding

Energy welding achieves vascular anastomosis by converting optical or electrical energy into thermal energy, which heats the anastomotic ends to induce partial denaturation and unwinding of the triple-helical collagen structure into randomly coiled polypeptide chains. This process facilitates synergistic aggregation of the denatured proteins, thereby bonding the vascular ends. Currently, the predominant energy sources in research are laser and high-frequency electric current [11, 32].

Laser welding

Laser light is a coherent light beam amplified by stimulated radiation. The active medium includes CO_2, Ar, Nd:YAG, He-Ne, and infrared diodes. In the 1970s, laser welding was gradually adopted for biological tissue repair, with the Nd:YAG laser being the first applied to vascular anastomosis [33, 34]. Over the past four decades, advancements in laser technologies have expanded their applications in vascular anastomosis. Researchers have identified key factors influencing the efficacy of laser-welded vascular anastomosis, including laser parameters (Wavelength, power output, and pulse width), tissue penetration depth, and welding duration. Optimal thermal effects for achieving robust anastomosis require a pulse width of 1 μs/min during vascular anastomosis [35]. Laser parameters vary significantly across different laser systems, and their interactions with specific biological tissues determine the penetration depth within the tissue. Typically, CO_2 lasers exhibit a penetration depth of 10-50 μm in vascular tissue, which is notably shallower compared to other laser types.

Laser welding offers advantages such as high precision, short operative time, absence of foreign body reactions, and a reduced risk of postoperative aneurysms. However, the high collagen fiber and hemoglobin content in vascular tissues result in elevated laser absorption coefficients and penetration depths, which may cause thermal damage to the vessel wall, compromise anastomotic strength, and impair surgical outcomes [36]. To address these limitations, researchers have employed reinforcement materials such as albumin, polylactic-co-glycolic acid (PLGA), and indocyanine green (ICG) to augment laser-mediated anastomosis [12, 37, 38]. Despite these advancements, laser-welded vascular anastomosis has not yet been adopted clinically, with improving initial anastomotic strength remaining the critical challenge for its widespread implementation.

High-frequency electric welding

High-frequency electric welding utilizes heat generated by high-frequency alternating current to thermally fuse tissues, as shown in **Figure 2**. The current is delivered via electrodes to achieve tissue cutting, coagulation, or closure. In 1962, Sigel and Acevedo successfully sealed linear vascular incisions using high-frequency current transmitted through bipolar electrocautery forceps [39]. During the 1990s, high-frequency electric welding technology advanced rapidly. Barry et al. used radiofrequency current combined with mechanical pressure to weld the carotid artery in dogs and investigated the effect of radiofrequency current on the mechanical and histological properties of the arterial wall [40]. However, this method has notable limitations: (1) Electrode-tissue adhesion: Removal of electrodes may disrupt the anastomotic seal; (2) Uncontrolled parameters: Difficulty in optimizing current intensity and anastomosis duration compromises outcomes [41, 42].

In summary, energy welding techniques face critical challenges in clinical applications, including imprecise thermal control, excessive thermal damage, and insufficient anastomotic strength, necessitating continuous technological refinement and innovation.

Photochemical tissue bonding

Photochemical tissue bonding (PTB) is a sutureless anastomosis technique that achieves tissue adhesion through laser-activated photochemical reactions. This method induces electron transfer between photosensitizing chemicals and biological tissues, leading to covalent crosslinking of collagen molecules at the anastomotic site. In 2007, O'Neill and Winograd from Harvard University pioneered this technique, successfully anastomosing rat femoral arteries by applying photosensitizers to both vascular ends and irradiating them with a 532 nm laser (power density: 0.5 W/cm^2, energy density: 150 J/cm^2) [43]. During the 30-second irradiation on each side, an intraluminal catheter was inserted to maintain vascular patency.

Unlike energy welding, which depends on thermal energy, PTB relies on photochemical crosslinking, eliminating thermal damage to surrounding tissues. The technique employs 532 nm laser light combined with photosensitizers to initiate collagen covalent bonding, enabling rapid and robust tissue adhesion. Commonly used photosensitizers include Rose Bengal, Riboflavin-5-Phosphate (R5P), Methylene Blue (MB), and N-2-Hydroxypyridine (N-HTP) [44, 45].

As an advancement over laser welding, PTB addresses critical limitations such as thermal injury and high-energy laser requirements. However, challenges persist, including high operational costs and difficulties in laser parameter optimization, necessitating further research for clinical translation.

Microvascular stapler anastomosis

Microvascular stapler anastomosis refers to a vascular anastomosis method that replaces sutures with specialized devices, primarily categorized into staples, magnets and rings based on vascular eversion fixation mechanisms, as shown in **Figure 3**.

Staples

Staple-based anastomosis achieves vascular connection by mechanically pressing surgical staples (metal or polymeric) into both vascular

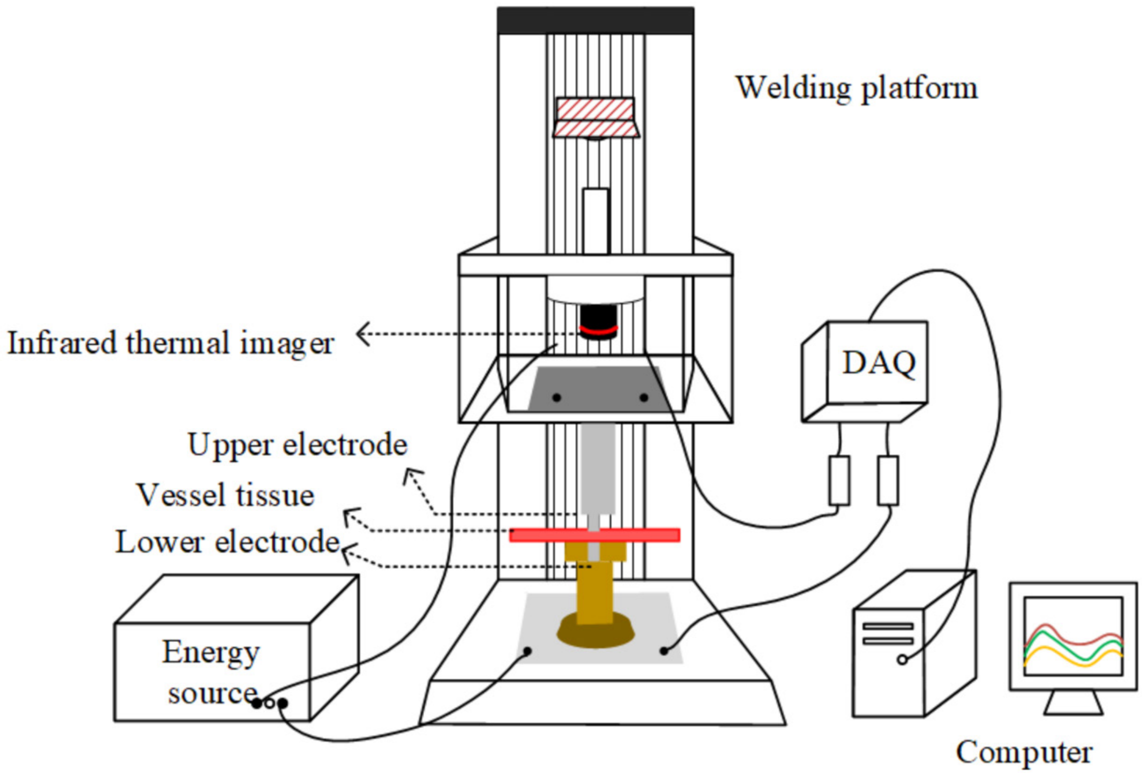

Figure 2. High-frequency electric welding: The treated vessel tissue is placed between the upper and lower electrodes, and the upper and lower electrodes deliver energy to the vessel tissue. The infrared thermal imager begins to record the tissue temperature until the end of the welding experiment [42].

ends. These stapling devices typically comprise a handle, anvil head, cartridge, and staples. During anastomosis, staples are deployed in a staggered arrangement to seal potential leaks. In 1908, Hungarian surgeon Hümér Hültl innovated the first surgical stapler, inspired by regular staplers, modifying the anvil to create B-shaped staples upon compression [46]. This design ensures secure vascular fixation while preserving blood supply and nutrient delivery to stapled tissue margins.

Compared to sutures, staples offer lower infection rates and shorter operative times, making them widely used in gastrointestinal anastomosis [47]. However, there are several factors that limit their application in vascular anastomosis [48]. Firstly, the vascular needs to be valgus 180°, which increases the risks of anastomotic stenosis; Secondly, permanent staples may induce chronic inflammation or foreign body reactions; Lastly, improper staple placement can cause impaired healing or functional compromise.

Magnets

Magnetic anastomosis achieves vascular reconstruction by implanting magnetic devices at both vascular ends, enabling instantaneous coupling via magnetic attraction. In 1978, Obora et al. first performed end-to-end venous anastomosis in rats using magnetic rings [49]. In 2004, Erdmann et al. successfully applied magnetic rings for side-to-side arterial and venous anastomosis in foxhounds. Since then, magnetic anastomosis has significantly evolved [50]. To date, it has been validated in animal models for end-to-end anastomosis, side-to-side anastomosis, and artificial vascular grafting [15, 50, 51].

Magnetic Anastomosis has several advantages, including simplified operation, shortened operative time, and reduced complications, such as anastomotic leakage. However, its limitation include challenges in repositioning once the magnetic rings are coupled. Suboptimal alignment necessitates device removal and replacement, potentially increasing surgical trauma.

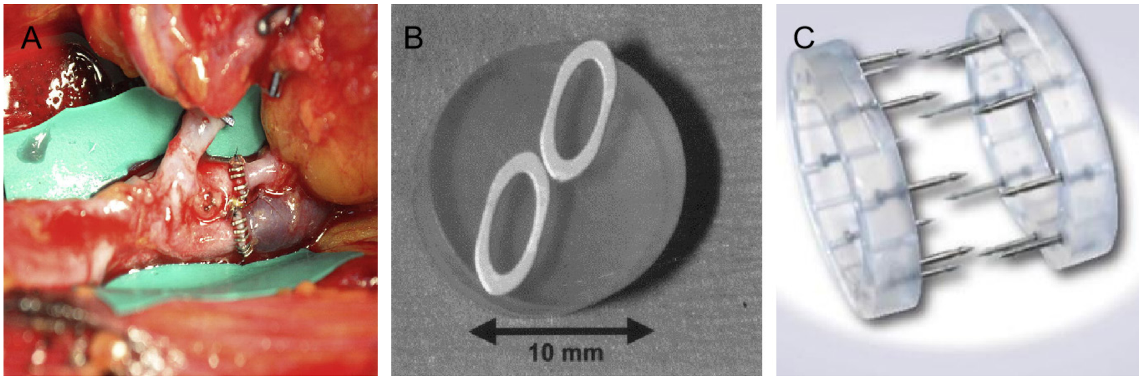

Figure 3. Typical anastomosis devices of microvascular stapler anastomosis [50, 59]: (A) Staples; (B) Magnetic rings; (C) GEM Coupler.

Rings

Ring-type staplers primarily consist of two coupling rings. During anastomosis, vessels are threaded through the rings, everted, and fixed, followed by ring apposition for end-to-end vascular connection. Based on eversion fixation methods, these staplers are classified into needle-ring and needleless types.

Needle-ring staplers feature alternating needles and holes on each ring. Vessels are everted and secured onto the needles, achieving anastomosis through needle-hole coupling. In 1900, Erwin Payr designed a magnesium ring to assist anastomosis by threading the proximal vessel through the ring, everting its margin, and inserting it into the dilated distal vessel [52]. In 1960, Holt and Lewis first proposed paired needle-perforated rings [53]. Subsequently, Ostrup and Berggren refined this design in 1986 by alternating needle-hole distribution, developing the Unilink system—the precursor to the clinically established GEM Coupler [54]. The GEM Coupler offers advantages, including ease of operation, precise intimal apposition, absence of intraluminal foreign bodies, and reduced anastomotic leakage. Although initially deemed suitable only for venous anastomosis due to arterial wall elasticity and thickness, ongoing research explores its arterial applicability.

Needleless staplers employ inner and outer rings: vessels are threaded through the inner ring, everted, and secured via outer ring fixation. Li et al. developed a novel device with two connecting rings and two posterior rings, addressing efficiency and reliability limitations of manual sutures [14]. Although needleless designs eliminate the use of metal needles, reducing the damage to the vascular intima, their clinical potential remains unvalidated due to insufficient long-term animal studies and human trials.

From the perspective of materials, the three types of stapling devices predominantly utilize non-degradable materials such as polyethylene, stainless steel, and titanium. Their long-term retention impairs physiological vascular function and restricts remodeling at the anastomotic sites. Consequently, researchers are exploring biodegradable materials for vascular staplers. These materials provide short-term mechanical support during anastomosis and are gradually absorbed post-healing, effectively preventing long-term implant-related complications. Additionally, their degradation releases bioactive substances that promote vascular regeneration and repair. Needleless designs eliminate metallic components but lack validation in long-term animal and clinical studies. Zhang Qiong and Xu Shuogui developed biodegradable shape memory sleeve-needle ring system for anastomosis (PLA needle rings and polycaprolactone (PCL) sleeves), achieving successful rabbit jugular vein anastomosis [55]. Li Zhuoqun et al. fabricated a 3D-printed polypropylene-based biodegradable stapler, evaluating its hypertension tolerance and clinical potential in rabbit models. Ryan Brewster et al. designed a biodegradable stapler composed of polylactic acid (PLA) and copolymers with dual inner and outer rings, successfully anastomosing porcine carotid arteries [57].

However, these biodegradable vascular staplers still face multiple technical challenges. Firstly, mismatched degradation kinetics and vascular healing timelines remain a critical issue. For instance, PCL exhibits a degradation period of 12-24 months, far exceeding the typical 3-6 months required for vascular remodeling. This discrepancy leads to premature mechanical failure or delayed material absorption, compromising anastomotic integrity. Secondly, long-term safety validation remains insufficient. Degradation byproducts may impair vascular repair through mechanisms including local toxicity, metabolic burden, and immune reactions. Consequently, systematic long-term biocompatibility evaluations are imperative before clinical adoption, particularly to assess chronic risks like ectopic calcification and systemic metabolic disturbances.

III Conclusion

Vascular anastomosis, as a cornerstone of surgical practice, has undergone over a century of evolution. The emergence of robotic-assisted anastomosis, biomedical adhesives, energy welding, and stapling devices has driven transformative technological breakthroughs. Concurrently, advancements in biodegradable materials promise to accelerate the refinement and clinical translation of these techniques.

Traditional manual sutures, recognized as the gold standard, have achieved 0.1 mm-level precision through microsurgical innovations and remain the most widely used clinical method. However, manual sutures remain limited by operator dependency, prolonged operative durations, and high postoperative stenosis rates, which necessitate urgent solutions. The rise of surgical robotics has mitigated operator-related variability, enhancing both precision and procedural complexity. Sutureless techniques—including biomedical adhesives, energy welding, and stapling devices—have reduced anastomotic time to 5-10 minutes. Furthermore, the integration of biodegradable materials into sutures and staplers has emerged as a pivotal research direction to address foreign body retention. In addition, some researchers have explored combining various anastomosis methods, such as manual sutures, biomedical adhesives, magnetic anastomosis and energy welding to optimize the joint application of multiple anastomosis technologies.

Despite their unique advantages, all anastomotic techniques face distinct challenges. Surgical robotic systems, while achieving high precision, are hindered by prohibitive costs, lack of haptic feedback, and steep learning curves. Energy welding methods remain clinically unvalidated due to thermal collateral damage and insufficient anastomotic strength. Non-degradable materials such as staples and magnetic rings provoke chronic inflammation upon prolonged retention, while biodegradable alternatives require optimization to balance mechanical performance with degradation kinetics. Specifically, the degradation rates of biodegradable materials need to be regulated to match the healing cycle of blood vessels (3-6 months). Energy welding for immediate anastomotic sealing can be combined with biomedical adhesives for thermal protection, achieving both superior mechanical strength and minimized thermal injury to the anastomosis. Extensive animal experiments and clinical trials are needed to verify the long-term safety and effectiveness of these methods.

In conclusion, the future development of vascular anastomosis technology should focus on solving current technical bottlenecks, offering more efficient and safe solutions for the fields of cardiovascular disease, trauma treatment, and organ transplantation through three key directions of material innovation, technology integration, and clinical transformation.

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