

# Advances in Wound Closure Technologies: A Comprehensive Multi-Decadal Review

Prathamesh Dhananjay Thorat<sup>1</sup>, Shubhangi Dipak Narode<sup>2</sup>, Payal Vasant Bhosale<sup>3</sup>,  
Mansi Vikas Saudagar<sup>4</sup>, Priyanka Anil Sanap<sup>5</sup>, Deshmukh D. B<sup>6</sup>, Unde R. S<sup>7</sup>

Mrs. Saraswati Wani College of D Pharmacy Ganegaon, Rahuri, Ahilyanagar<sup>1,2,3,4,5</sup>

Guide, Mrs. Saraswati Wani College of D Pharmacy Ganegaon, Rahuri, Ahilyanagar<sup>6,7</sup>

**Abstract:** Wound closure remains a cornerstone of surgical excellence and emergency medical intervention. Over the past several decades, the field has evolved from rudimentary mechanical approximation techniques to highly engineered, biomimetic, and intelligent theragnostic systems. This comprehensive review article details the historical trajectory, material science, biomechanical principles, and clinical outcomes of modern wound closure devices. We analyze traditional macro-mechanical benchmarks such as monofilament and multifilament sutures, mechanical staples, and hemostatic clips, alongside advanced non-invasive options including micro-anchor matrices and pressure-sensitive zip devices. Furthermore, we dissect the chemical kinetics and biological interactions of topical cyanoacrylate adhesives, fibrin glues, and catechol-functionalized hydrogels. Finally, we explore the cutting-edge frontier of smart closures equipped with flexible bioelectronics for real-time physiological monitoring and controlled drug-eluting capabilities. By assessing tensile strength, infection mitigation, cosmetic outcomes, and health economics, this review provides clinical practitioners and biomedical engineers with a unified framework for matching optimal closure modalities to specific anatomical and physiological demands. [1]

**Keywords:** Wound closure

## I. INTRODUCTION

The primary objective of any wound closure intervention is the rapid, secure, and anatomically precise reapproximation of disrupted tissue layers. Effective wound closure serves multiple vital physiological functions: it establishes rapid hemostasis, preserves mechanical integrity against extrinsic shear forces, minimizes metabolic stress on healing margins, and erects a robust physical barrier against microbial invasion. Historically, the management of cutaneous and deep-tissue disruptions relied heavily on basic structural fixation. While linear mechanical stability remains crucial, contemporary surgical sciences demand modalities that actively promote microvascular regeneration, mitigate excessive foreign-body inflammatory responses, and yield optimal cosmetic and functional long-term outcomes. [2]

Dynamic stress distribution across a healing incision is a fundamental biomechanical requirement. Tissues subjected to constant movement or high intrinsic tension—such as those overlying joints or abdominal walls—are highly susceptible to micro-tearing, ischemic necrosis, and surgical site dehiscence if the closing modality concentrates forces at discrete, isolated focal points. Conversely, uniform tension distribution facilitates cellular homeostatic restoration, allowing fibroblasts, endothelial cells, and keratinocytes to migrate unimpeded across the wounded cleft. Concurrently, the prevention of Surgical Site Infections (SSIs) stands as a paramount metric of clinical success, as SSIs drastically compound institutional healthcare costs, prolong hospital stays, and escalate patient morbidity. Consequently, the ideal modern wound closure device must balance mechanical tenacity with biological compatibility, mitigating dead-space formation while acting as an impenetrable seal against macroscopic pathogens. [3]



## **II. MACRO-MECHANICAL BENCHMARKS: MATERIAL SCIENCE OF SUTURES**

### **2.1 Monofilament versus Multifilament Configurations**

Sutures represent the most enduring legacy in surgical toolkits, structurally categorizable by their physical braid-layout into monofilament and multifilament topologies. Monofilament sutures consist of a single solid strand of polymeric material. This uniform, smooth profile offers the critical clinical advantage of minimal tissue drag, drastically reducing the micro-friction exerted on delicate structures during placement. Furthermore, the lack of interstitial voids within a monofilament strand eliminates the risk of bacterial 'wicking'—a phenomenon where pathogens reside and propagate within the interstitial spaces of a braid, shielded from host immune cells and systemic antibiotics. However, monofilaments exhibit structural memory, making them inherently stiffer, less pliable, and more prone to knot slippage under cyclic mechanical loading. [4]

In contrast, multifilament sutures comprise multiple interwoven micro-strands. This braided configuration imparts exceptional flexibility, superior handling characteristics, and unparalleled knot security, as the texturized surfaces of the intersecting strands interlock under tension. These structural benefits come at a cost: the structural capillarity of braided constructs increases the localized pathogen burden if a surgical field becomes contaminated. Consequently, multifilament configurations are frequently contraindicated in infected or highly contaminated environments, whereas they remain highly favored in clean deep-tissue closures where maximum knot reliability and high tensile endurance are mandatory. [5]

### **2.2 Degradation Kinetics of Synthetic Bioresorbable Polymers**

The development of synthetic bioresorbable polymers revolutionized deep-tissue management by eliminating the need for subsequent device extraction and mitigating long-term foreign-body reactivities. The primary synthetic classes include Polyglyactin 910 (PGLA), Polyglycolic Acid (PGA), Polydioxanone (PDS), and Poliglecaprone 25. These materials undergo predictable chemical degradation via hydrolysis, wherein water molecules cleave the polymer's ester backbones, converting the complex matrix into water-soluble, biocompatible monomers that are subsequently metabolized or excreted by the host organism. [6]

The temporal degradation profile must align precisely with the tissue's intrinsic healing curve. For instance, Poliglecaprone 25 exhibits rapid tensile strength degradation, losing roughly 50% of its mechanical hold within 7 to 10 days, making it ideal for fast-healing mucosal linings or superficial dermal closures. In contrast, Polydioxanone (PDS) maintains high structural integrity for over 6 weeks, providing extended structural support required for slow-healing fascia, load-bearing abdominal walls, and patients with compromised wound-healing kinetics, such as those suffering from advanced diabetes or uncontrolled peripheral vascular disease. [7]

## **III. ADVANCED NON-INVASIVE MECHANICAL DEVICES**

### **3.1 Micro-Anchor Arrays**

To entirely avoid the cellular trauma and localized ischemia induced by traditional needle punctures, modern biomedical engineering has pioneered non-invasive mechanical closure matrices. Chief among these are micro-anchor arrays, exemplified commercially by platforms such as MicroMend. These devices utilize a technical architecture consisting of a flexible, medical-grade adhesive backing integrated with multiple microscopic, stainless-steel tiny staples or anchors extending from the margins. When applied across a properly aligned, clean wound edge, the micro-anchors securely insert into the epidermal and superficial dermal layers without penetrating deep enough to excite pain-sensing nociceptors or disrupt major subdermal vascular networks. [8]

The macro-distribution of forces achieved by micro-anchor arrays represents a major paradigm shift. Instead of concentrating the entire closure stress onto distinct points spaced centimeters apart (as seen in interrupted suturing), the micro-anchor grid spreads the transverse forces uniformly across the entire length of the incision line. This uniform anchoring completely eliminates the 'railroad track' scarring patterns commonly associated with traditional metal staples or bulky sutures. Clinical studies have shown that micro-anchor systems drastically accelerate closure



velocities, decrease intraoperative operator dependencies, and yield aesthetic profiles that closely rival or exceed those achieved by meticulously executed intradermal running closures. [9]

### **3.2 Topical Pressure-Sensitive Surgical Zipper Matrices**

Another innovative milestone in non-invasive wound management is the topical pressure-sensitive zipper matrix, exemplified by systems like Zip Stitch. These advanced systems replace invasive piercing mechanisms with a pair of parallel, high-tack, biocompatible hydrocolloid adhesive strips linked by a series of adjustable, micro-ratcheting plastic structural ties. The adhesive components are placed firmly on either side of the isolated wound gap, and the operator gently draws the ratcheting ties inward, providing a calibrated, highly customizable approximation force that perfectly closes the epidermal margins. [10]

The primary clinical value of surgical zippers lies in their ability to act as an external dynamic shock absorber. When the patient moves, bends, or coughs, the flexible plastic ties expand and contract slightly, absorbing the localized shear forces and protecting the fragile, regenerating granulation tissue beneath from mechanical disruption. Because there is no breach of the intact skin barrier around the incision, the incidence of tracking infections is practically neutralized. Furthermore, these systems allow for rapid, completely painless removal in outpatient environments, eliminating the anxiety, discomfort, and clinical overhead expenses associated with post-operative suture cutting or staple extraction. [11]

## **IV. CHEMICAL AND BIOLOGICAL TOPICAL ADHESIVES**

### **4.1 Polymer Chemistry of Advanced Cyanoacrylates**

Topical chemical adhesives have emerged as highly efficient alternatives for closing clean, low-tension lacerations. The polymer chemistry governing these liquid agents centers on cyanoacrylate compounds, primarily N-butyl cyanoacrylate and 2-octyl cyanoacrylate. When exposed to ambient moisture or anionic substances on the skin's surface, these monomeric formulations undergo a rapid, highly exothermic polymerization reaction. The monomers quickly link to form long, robust polymeric chains that bind tightly to the outer keratinized layers of the epidermis, creating a tough, flexible surface seal over the wound margins. [12]

The clinical characteristics of the adhesive layer depend heavily on the length of the underlying alkyl molecular side-chain. Short-chain formulations like methyl cyanoacrylate polymerize rapidly but form a brittle, rigid crystalline structure that breaks easily when deformed; furthermore, they release high concentrations of histotoxic degradation byproducts, causing significant tissue inflammation. Modern medical-grade 2-octyl cyanoacrylate incorporates a significantly longer alkyl chain, resulting in a flexible, plasticized barrier layer that can bend repeatedly without cracking. This long-chain configuration drastically slows down internal degradation rates, reducing localized tissue toxicity while maintaining an optimal microbial barrier that effectively repels common hospital pathogens for 7 to 10 days. [13]

### **4.2 Fibrin Glues and Mussel-Inspired Hydrogels**

While cyanoacrylates are restricted to external epidermal surfaces due to their potential toxicity in deeper tissues, biological and biomimetic adhesives are specifically formulated for deep internal applications. Fibrin glues copy the natural human coagulation cascade by combining concentrated fibrinogen with active thrombin and calcium chloride at the point of application. This mixture creates an instantaneous cross-linked fibrin matrix that adheres well to moist internal tissues, effectively sealing delicate vascular lines, preventing cerebrospinal fluid leaks, and providing excellent localized hemostasis. However, traditional fibrin glues possess low shearing strength, making them poorly suited for sealing high-pressure arterial vessels or closing structurally demanding load-bearing planes. [15]

To overcome these mechanical limitations in wet environments, researchers have turned to biomimetic strategies, specifically mussel-inspired catechol-functionalized hydrogels. Marine mussels naturally secrete specialized foot proteins that bind tightly to submerged, wave-battered rocks using the unique amino acid L-3,4-



dihydroxyphenylalanine (DOPA). By grafting these active catechol functional groups onto biocompatible synthetic hydrogels (such as polyethylene glycol or modified chitosan), scientists have synthesized wet-tolerant tissue adhesives. These advanced hydrogels form strong covalent bonds with the host tissue's proteins even when completely submerged in active blood or physiological fluids, presenting a promising alternative for internal organ closures, advanced cardiovascular sealing, and complex fetal surgical interventions. [16]

## **V. SMART THERANOSTIC CLOSURES AND FUTURE FRONTIERS**

### **5.1 Bioelectronic Monitoring Networks**

The frontier of wound closure engineering focuses on converting passive structural devices into smart Theranostic systems. These next-generation devices integrate flexible, stretchable bioelectronic micro-sensors directly into the structural matrix of sutures, mesh networks, or adhesive strips. These embedded sensor networks continuously track the biochemical environment of the healing tissue, offering real-time data that can identify complications long before visible macroscopic symptoms emerge. [17]

Changes in local tissue pH, electrical impedance, and temperature provide excellent indicators of wound status. A sudden rise in localized temperature, for example, typically signals the onset of acute inflammation or early-stage bacterial colonization. Concurrently, bacterial metabolic activity causes measurable shifts in local pH, while tissue edema alters electrical impedance across the wound margin. By linking these flexible sensors to small, bio-compatible wireless telemetry modules, smart closures can transmit real-time diagnostic alerts directly to clinician monitoring dashboards or patient mobile applications, enabling immediate clinical assessment and proactive intervention. [18]

### **5.2 Programmable Drug-Eluting and Automated Structural Matrices**

Beyond real-time diagnosis, smart closures are designed to actively treat localized complications through programmable drug-eluting matrices. These systems incorporate specialized nanostructured elements—such as electrospun core-shell nanofibers, mesoporous silica nanoparticles, or temperature-sensitive liposomes—directly into the closing material. These nanostructures can be loaded with specific therapeutic agents, including silver nanoparticles, broad-spectrum antibiotics, localized anesthetics, or targeted growth factors like Vascular Endothelial Growth Factor (VEGF) and Platelet-Derived Growth Factor (PDGF). [19]

The release kinetics of these therapeutic payloads can be carefully controlled. The matrix can be engineered to deliver a steady, sustained dose over several days to maintain a sterile field, or programmed to trigger drug release only in response to specific biochemical cues, such as an infection-induced pH shift. Additionally, advanced research is exploring the use of shape-memory polymers (SMPs). When exposed to body heat or specific light wavelengths, these advanced polymers undergo a pre-programmed structural change, generating a gentle, autonomous contraction force that helps approximate deep wound margins, minimizing the need for manual tension adjustments during complex surgical procedures. [20]

## **VI. COMPARATIVE SELECTION MATRIX**

To assist clinical teams and biomedical engineers in selecting the most appropriate modality, the following matrix compares the performance profiles, mechanical strengths, deployment metrics, and primary indications for each class of wound closure technology.

| Technology Class     | Tensile Strength | Deployment Speed | Microbial Barrier & Primary Indications                         |
|----------------------|------------------|------------------|-----------------------------------------------------------------|
| Traditional Sutures  | Very High        | Moderate / Slow  | Poor (Unless Treated)   Deep Fascia, High-Tension Muscle Layers |
| Surgical Staples     | High             | Rapid            | Poor   Scalp Lacerations, Orthopaedic Incisions                 |
| Topical Adhesives    | Low              | Very Rapid       | Excellent Seal   Low-Tension Facial Cuts, Pediatrics            |
| Non-Invasive Zippers | Moderate         | Rapid            | Excellent Seal   Arthroplasty Incisions, Fragile                |



|                    |          |          |                                                           |
|--------------------|----------|----------|-----------------------------------------------------------|
|                    |          |          | Skin                                                      |
| Smart Theranostics | Variable | Moderate | Excellent Integrated   High-Risk Surgical Sites, Research |

[21]

## VII. CONCLUSIONS AND TRANSLATIONAL HORIZONS

The field of wound closure has evolved far beyond basic mechanical tissue fixation. Contemporary solutions combine advanced polymer engineering, smart electronics, and biological systems to support the natural healing process actively. While traditional sutures and staples remain indispensable for deep, high-tension structural repairs, non-invasive mechanical devices and topical adhesives have significantly improved the care landscape for superficial closures by optimizing tension distribution, lowering infection rates, and enhancing patient comfort.

Moving forward, the successful translation of these technologies from research laboratories to routine clinical use relies on refining smart theranostic platforms. Overcoming manufacturing challenges, ensuring regulatory compliance, and establishing cost-effective production methods will allow these responsive, intelligent devices to become standard tools in modern surgical care. By continuously bridging the gap between material science and clinical medicine, the next generation of wound closure devices will continue to lower post-operative complications, optimize healthcare delivery, and significantly improve long-term patient outcomes.

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