

Complex Wound Closure: Surgical Principles, Adjunctive Technologies, And Emerging Strategies

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ABSTRACT

Complex wound closure remains a major challenge in reconstructive surgery because wound healing depends on coordinated cellular, molecular, vascular, infectious, and mechanical factors. Large traumatic defects, chronic wounds, postoperative dehiscence, irradiated wounds, diabetic ulcers, spinal wounds, chest wall defects, and wounds in medically compromised patients frequently fail to heal through standard closure methods. Successful management requires careful assessment of wound etiology, vascularity, contamination, tissue loss, tension, patient comorbidities, and reconstructive goals. Traditional strategies include primary closure, delayed primary closure, secondary intention healing, skin grafting, local tissue rearrangement, and flap reconstruction. Adjunctive modalities such as negative pressure wound therapy, incisional negative pressure therapy, skin stretching systems, dermal matrices, bioengineered scaffolds, and smart dressings have expanded the reconstructive armamentarium. Among these, negative pressure wound therapy has become one of the most widely adopted tools for complex wound management because it stabilizes the wound environment, reduces edema, promotes granulation tissue, and may decrease surgical site complications. However, no single technique is universally appropriate. Complex wound closure should be individualized according to wound biology, patient risk factors, anatomical location, functional demands, and available reconstructive resources. This review summarizes current principles, surgical options, adjunctive technologies, and future directions in complex wound closure.

KEYWORDS: complex wound closure; wound healing; negative pressure wound therapy; flap reconstruction; skin grafting; smart dressings; bioengineered scaffolds; chronic wounds; reconstructive surgery.

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INTRODUCTION

Wound closure is not merely the approximation of skin edges; it is the restoration of tissue continuity under biologically and mechanically favorable conditions. Complex wounds are those in which conventional primary closure is limited by tissue loss, infection, ischemia, high tension, exposed critical structures, chronic inflammation, radiation injury, systemic disease, or anatomic complexity. These wounds are commonly encountered after trauma, oncologic resection, spinal surgery, chest wall reconstruction, vascular disease, diabetic ulcers, pressure injuries, burns, and postoperative dehiscence.

Normal wound healing involves hemostasis, inflammation, proliferation, angiogenesis, re-epithelialization, extracellular matrix deposition, and remodeling [1,2]. Disruption of any phase can lead to delayed healing or chronicity, particularly in patients with diabetes, malnutrition, vascular disease, immunosuppression, infection, smoking, obesity, or repeated surgical trauma [3,4]. Therefore, complex wound closure requires a strategy that addresses both the wound and the patient.

Contemporary management has moved beyond the reconstructive ladder toward a reconstructive decision-making framework that integrates wound biology,

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mechanical forces, tissue availability, and adjunctive technologies. Evidence-based wound closure principles emphasize tension reduction, adequate vascularity, dead-space control, infection management, and selection of the simplest reliable technique that achieves durable closure [5,6].

METHODS

This narrative review was developed from the provided literature synthesis on complex wound closure. Included studies and reviews addressed wound healing mechanisms, negative pressure wound therapy, surgical closure techniques, flap reconstruction, complex spinal and chest wounds, skin stretching systems, bioengineered scaffolds, smart dressings, and emerging wound technologies.

The manuscript prioritizes clinically applicable concepts for reconstructive surgery and organizes the evidence by wound assessment, closure method, adjunctive therapy, emerging innovation, and future research needs. References are presented in numerical order according to first appearance in the text.

Biological Basis of Complex Wound Healing

The biological process of wound healing requires coordinated communication between platelets, neutrophils, macrophages, keratinocytes, fibroblasts, endothelial cells, extracellular matrix components, and stem cell populations [1]. In uncomplicated wounds, these processes lead to progressive re-epithelialization, granulation tissue formation, collagen deposition, and scar remodeling.

Complex wounds often deviate from this sequence. Persistent inflammation, bacterial biofilm, inadequate oxygenation, poor perfusion, repetitive trauma, mechanical tension, or systemic metabolic dysfunction can arrest the wound in a non-healing state [3,4]. Chronic wounds are particularly characterized by prolonged inflammation, protease imbalance, senescent fibroblasts, impaired angiogenesis, and deficient extracellular matrix organization.

Mechanical forces also influence healing. Excessive tension across a closure increases ischemia at the wound edge, promotes dehiscence, widens scars, and may compromise flap or graft survival. Conversely, controlled mechanical stimulation can promote cellular proliferation and matrix remodeling, which explains the rationale for tension-reducing closure, skin stretching systems, and certain mechanobiologic devices.

Initial Assessment of the Complex Wound

The first step in complex wound closure is defining why the wound is complex. Assessment should include wound etiology, size, depth, contamination, vascularity, exposed structures, previous surgery, radiation history, local tissue availability, and functional requirements. A wound with exposed tendon, bone, joint, vessel, nerve, prosthesis, mesh, or hardware requires a different strategy than a superficial granulating wound.

Patient-related factors must be evaluated simultaneously. Diabetes, peripheral vascular disease, renal failure, malnutrition, obesity, smoking, corticosteroid use, chemotherapy, immunosuppression, and infection significantly affect healing potential. Closure performed without correcting modifiable risk factors may fail despite technically appropriate surgery.

The wound should be assessed for infection, necrosis, biofilm, dead space, drainage, and tension. Debridement is necessary when nonviable tissue is present. Adequate wound bed preparation is essential before definitive closure, whether the final plan is primary closure, grafting, flap reconstruction, or device-assisted closure.

Principles of Surgical Closure

The essential principles of complex wound closure include adequate debridement, hemostasis, vascularized tissue coverage, tension reduction, dead-space obliteration, infection control, and durable soft-tissue reconstruction. In selected cases, direct closure is appropriate, but only when it can be achieved without excessive tension and with well-vascularized wound edges.

When primary closure is unsafe, delayed primary closure may be considered after serial debridement and wound optimization. Secondary intention healing may be appropriate for small wounds in favorable locations, but it is often inadequate for large wounds, wounds over joints, exposed critical structures, or areas where contracture would impair function.

Skin grafts are useful when the wound bed is vascularized and free of exposed tendon without paratenon, bone without periosteum, cartilage without perichondrium, or hardware. Flaps are preferred when vascularized tissue is required to cover exposed structures, obliterate dead space, resist infection, or improve functional durability.

Negative Pressure Wound Therapy

Negative pressure wound therapy has become one of the most important adjuncts in complex wound management. It applies controlled subatmospheric pressure to the wound through a sealed dressing system. Its proposed mechanisms include removal of exudate, reduction of edema, stabilization of the wound environment, improved perfusion, macrodeformation, microdeformation, bacterial burden reduction, and stimulation of granulation tissue [7–9].

NPWT is particularly useful in traumatic wounds, infected wounds after debridement, wounds with significant exudate, open abdominal or extremity wounds, and wounds awaiting grafting or flap coverage. It can serve as a bridge to definitive reconstruction by improving the wound bed and allowing serial reassessment.

Incisional negative pressure wound therapy has also gained importance for high-risk closed surgical incisions. Systematic review evidence suggests that it may reduce surgical site complications such as infection, seroma, and dehiscence in selected high-risk patients [10]. However, NPWT should not

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be considered a substitute for appropriate debridement, vascularized coverage, or infection control. Its effectiveness depends on correct indication, adequate seal, appropriate pressure settings, and frequent reassessment.

Complex Spinal and Chest Wall Wounds

Spinal wounds are challenging because of high tension, long incisions, hardware exposure, dead space, prior radiation, obesity, diabetes, and the consequences of infection around instrumentation. Plastic surgery involvement may be beneficial in high-risk cases, particularly when muscle or fasciocutaneous flap coverage is required to reduce dead space and protect hardware [11,12].

Complex chest wall wounds similarly require durable coverage over vital structures, ribs, sternum, prosthetic material, or exposed hardware. In these cases, NPWT may assist in temporary stabilization or infection control, but definitive reconstruction frequently requires regional muscle flaps, fasciocutaneous flaps, or free tissue transfer depending on defect location and size [13].

The role of early reconstructive involvement is especially important in these anatomical regions. Delayed referral after repeated failed closures may worsen tissue quality and increase reconstructive complexity.

Skin Stretching and Distraction-Based Closure

Skin stretching systems use the biomechanical properties of skin creep and stress relaxation to gradually approximate wound edges. These devices are useful when direct closure would create excessive tension but adjacent skin remains viable and mobile. They may reduce the need for grafts or flaps in selected wounds.

Clinical reports describe the use of simple skin stretching systems combined with vacuum sealing drainage for complex wounds, showing that mechanical approximation can facilitate closure in wounds that might otherwise require more extensive reconstruction [14]. Modified distraction-tension devices, including Ilizarov-based systems, have also been used for limb wounds that are difficult to cover with flaps [15].

These strategies are particularly useful when flap options are limited, donor sites are poor, or patient comorbidities make major reconstruction undesirable. However, they require careful monitoring because excessive tension may cause skin necrosis, pain, ischemia, or wound edge breakdown.

Fascial and Cutaneous Meshing Techniques

In some complex wounds, closure is limited by tension in both deep fascia and skin. Fascial and peri-incisional cutaneous meshing techniques have been described as a method to increase tissue compliance and facilitate closure in difficult soft-tissue defects [16]. These methods may be particularly useful in distal extremity wounds where tissue laxity is limited.

The concept is similar to tension redistribution: rather than forcing linear closure under high stress, meshing allows controlled expansion and reduces focal tension. Although

promising, this approach requires appropriate patient selection and more comparative data to define its role relative to flaps, grafts, and skin stretching devices.

Skin Grafting

Split-thickness skin grafting is a reliable method for closing large superficial defects when the wound bed is healthy, vascularized, and free of infection. It is useful for traumatic wounds, granulating wounds after NPWT, donor sites, burns, and some chronic wounds after adequate preparation.

However, grafting is not appropriate over poorly vascularized structures or unstable wound beds. It also provides limited durability over pressure-bearing surfaces, joints, tendons, and irradiated or scarred tissue. Contracture, pigmentation changes, contour irregularity, and graft loss remain relevant limitations.

Full-thickness skin grafts provide better texture and contraction resistance but require smaller recipient beds and reliable vascularity. In complex wounds, skin grafting is often used after NPWT, dermal matrix placement, or flap reconstruction to complete closure.

Flap Reconstruction

Flap reconstruction remains the cornerstone for complex wounds with exposed critical structures, infection-prone dead space, irradiated tissue, or inadequate local vascularity. Flaps bring vascularized tissue into the wound, improve antibiotic delivery, obliterate dead space, protect hardware, and provide durable coverage.

Local flaps are useful when adjacent tissue is healthy and outside the zone of injury. Regional muscle flaps may be preferred for infected wounds, cavities, and exposed hardware because of their vascularity and bulk. Fasciocutaneous and perforator flaps provide pliable coverage with less muscle morbidity. Free flaps are required when local or regional options are unavailable or insufficient. The choice of flap depends on wound location, defect size, tissue requirements, recipient vessel availability, donor-site morbidity, and functional consequences. In reconstructive surgery, the goal is not simply closure but stable coverage that allows rehabilitation, ambulation, prosthetic use, or return to function.

Bioengineered Scaffolds and Dermal Matrices

Bioengineered scaffolds and dermal matrices attempt to reproduce aspects of the extracellular matrix and guide tissue regeneration. These materials may provide a temporary or permanent framework for cellular migration, angiogenesis, collagen deposition, and tissue integration [17,18].

Scaffold-based approaches are especially attractive in full-thickness wounds, chronic wounds, burns, and wounds where autologous tissue is limited. Some scaffolds are combined with growth factors, stem cells, antimicrobial agents, or nanomaterials to enhance regeneration [17–19].

Despite promising experimental and early clinical results, scaffold-based reconstruction remains limited by cost, variability in integration, infection risk, need for staged

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grafting, and lack of long-term comparative evidence. These technologies should be viewed as adjuncts that can expand options but do not replace fundamental principles of debridement, vascularity, and mechanical stability.

Smart Dressings and Bioadhesives

Smart dressings and bioadhesives represent an emerging shift toward responsive wound care. These technologies may monitor pH, temperature, glucose, moisture, oxygenation, or infection markers while also delivering drugs, electrical stimulation, or antimicrobial therapy [20–22].

Smart bioadhesives can potentially improve closure by combining mechanical adhesion with biologic activity. Wireless closed-loop dressings may allow real-time monitoring and on-demand treatment, reducing the delay between wound deterioration and clinical intervention [21]. Bioresorbable electrotherapy systems may further support healing through electrical stimulation and impedance monitoring [23].

Although these platforms are promising, most evidence remains preclinical or early clinical. Barriers include cost, scalability, regulatory approval, training, durability, data interpretation, and integration into clinical workflows.

Prophylactic Closure Strategies in High-Risk Patients

Complex wound closure is not only reactive; it can also be preventive. High-risk incisions may benefit from layered tension-reducing closure, quilting sutures, closed-suction drainage, incisional NPWT, prophylactic flap coverage, or early plastic surgery involvement.

Examples include obese patients undergoing spine surgery, irradiated chest wall wounds, breast surgery patients at risk for wound complications, and oncologic resections with dead space. In breast surgery, vacuum-assisted wound closure has

been evaluated as a method to improve healing and reduce wound-related complications in selected patients [24]. Risk stratification is essential. Prophylactic advanced closure may not be necessary for every patient, but it can be valuable when wound failure would expose hardware, delay adjuvant therapy, cause infection, or require major reoperation.

Proposed Management Algorithm

A practical algorithm for complex wound closure may include the following steps:

- 1. **Define wound complexity:** determine whether complexity is due to tissue loss, infection, ischemia, exposed structures, radiation, chronicity, or patient comorbidities.
- 2. **Optimize the patient:** address nutrition, glycemic control, smoking, vascular status, infection, edema, and systemic illness.
- 3. **Prepare the wound bed:** perform debridement, irrigation, culture-directed therapy when indicated, and control of contamination.
- 4. **Assess closure feasibility:** determine whether direct closure is possible without excessive tension.
- 5. **Select the simplest reliable option:** primary closure, delayed closure, grafting, local flap, regional flap, or free flap.
- 6. **Use adjuncts strategically:** apply NPWT, incisional NPWT, dermal matrices, skin stretching, or scaffolds when they improve the closure plan.
- 7. **Protect the reconstruction:** use offloading, immobilization, compression, drains, antibiotics when indicated, and close follow-up.
- 8. **Plan long-term function:** consider scar quality, joint motion, pressure tolerance, prosthetic use, recurrence risk, and secondary revision.

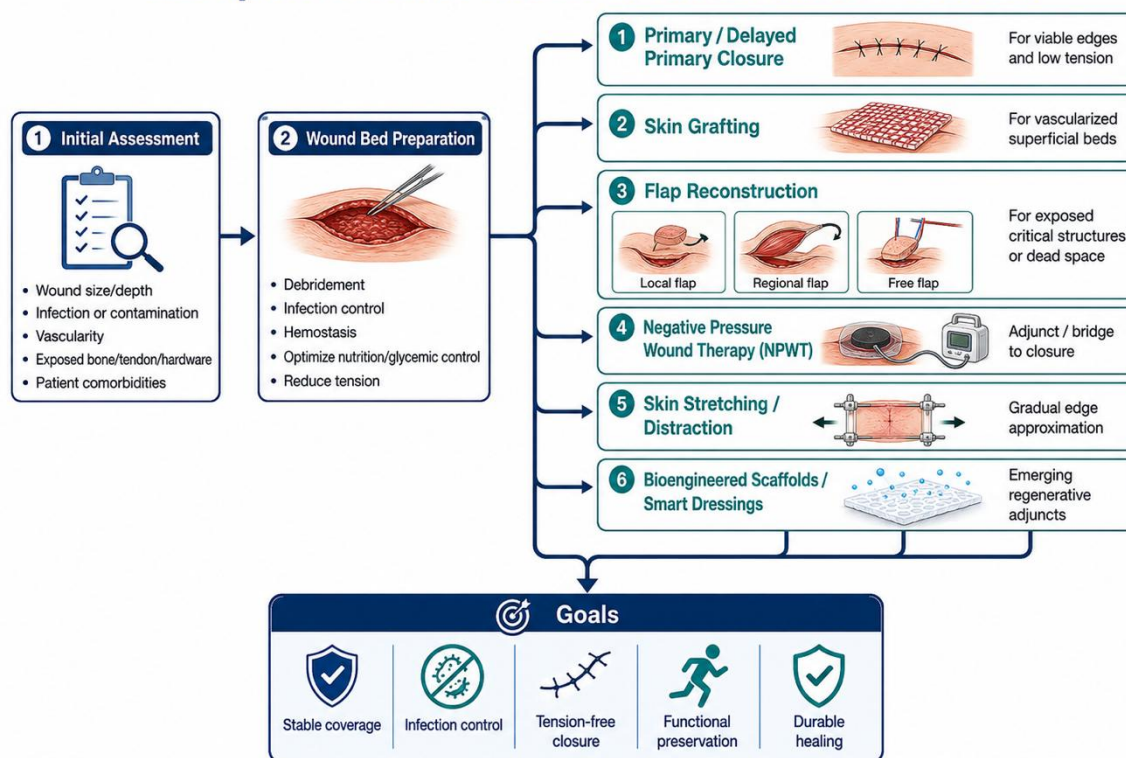
Table 1. Practical Selection of Closure Strategies for Complex Wounds

Closure strategy	Main indications	Key advantages	Main limitations	Surgical objective
Primary closure	Clean wounds with viable edges and minimal tension	Simple, fast, avoids donor-site morbidity	High risk of dehiscence if performed under tension, infection, or poor vascularity	Direct approximation of tissue with stable healing
Delayed primary closure	Contaminated or uncertain wounds after debridement and observation	Allows reassessment of tissue viability and infection control	Requires repeated wound care or return to operating room	Close the wound once the bed is clean and stable
Secondary intention healing	Small superficial wounds, concave areas, or patients unfit for surgery	Avoids operative morbidity	Slow healing, contraction, scar widening, poor durability in functional areas	Allow spontaneous granulation and epithelialization
Split-thickness skin graft	Large superficial defects with a vascularized wound bed	Covers broad areas efficiently; technically reliable	Fails over exposed bone, tendon, cartilage, vessels, hardware, or infected beds	Provide epithelial coverage over prepared tissue

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Closure strategy	Main indications	Key advantages	Main limitations	Surgical objective
Full-thickness skin graft	Smaller defects needing better texture, color, or less contraction	Better aesthetic match and less secondary contraction	Limited donor availability; requires excellent vascularity	Durable coverage for selected superficial defects
Local flap	Small to moderate defects with healthy adjacent tissue	Replaces “like with like”; preserves regional anatomy	Limited reach; unreliable if adjacent tissue is scarred, irradiated, or injured	Provide vascularized tissue without distant donor site
Regional muscle flap	Dead space, exposed hardware, infection-prone wounds, spinal or chest wall defects	Robust vascularity, obliterates dead space, improves infection control	Donor-site morbidity and possible functional loss	Protect deep structures and fill complex cavities
Fasciocutaneous/perforator flap	Defects requiring pliable durable soft-tissue coverage	Less muscle sacrifice; good contour and durability	Requires perforator knowledge and careful planning	Stable coverage with reduced donor morbidity
Free flap reconstruction	Large defects, exposed vital structures, failed local options, irradiated or hostile wounds	Imports healthy vascularized tissue from outside the injury zone	Microsurgical complexity, longer operative time, need for recipient vessels	Definitive reconstruction when local options are inadequate
Negative pressure wound therapy	Exudative wounds, post-debridement wounds, traumatic wounds, bridge to graft/flap	Reduces edema, promotes granulation, controls exudate, stabilizes wound bed	Not definitive for exposed critical structures; should not delay needed flap closure	Prepare or protect the wound before final flap closure
Incisional NPWT	High-risk closed incisions, obese/diabetic patients, spine, breast, or oncologic wounds	May reduce infection, seroma, and dehiscence	Cost, device dependence, and compliance	Protect a closed patient incision at high risk of failure
Skin stretching/distraction systems	Wounds where direct closure is possible only after gradual tissue recruitment	May avoid grafts or flaps; uses local tissue	Risk of edge ischemia, pain, necrosis, or device failure	Gradually reduce wound size and closure tension
Dermal matrices/bioengineered scaffolds	Full-thickness wounds, poor soft-tissue quality, staged reconstruction	Provides regenerative framework; may improve tissue integration	Cost, infection risk, variable take, often secondary grafting	Convert complex wound into graftable or more stable bed
Smart dressings/bioadhesives	Emerging use in chronic wounds or wounds needing monitoring	Potential real-time sensing and drug/electrical delivery	Mostly early clinical or preclinical evidence; cost and scalability concerns	Personalized wound monitoring and biologically active closure support

Complex Wound Closure: Schematic Overview



DISCUSSION

Complex wound closure requires a balance between surgical judgment and biologic optimization. The surgeon must determine whether the wound is ready for closure, what type of tissue is required, and whether adjunctive technology will improve the outcome. Failure often occurs when a wound is closed under tension, over infection, over necrotic tissue, or without adequate vascularity.

Negative pressure wound therapy has strong clinical utility, particularly as a bridge to closure or as protection for high-risk incisions. However, it should not delay necessary debridement or flap coverage. Similarly, smart dressings, scaffolds, and bioadhesives are promising but should be integrated into reconstructive planning rather than used as isolated solutions.

The reconstructive ladder remains useful, but complex wounds often require a more flexible reconstructive matrix. A small wound with exposed hardware may require a flap, whereas a large superficial wound may be managed successfully with NPWT and grafting. Therefore, wound depth, biology, and functional consequences are often more important than size alone.

Future research should focus on comparative effectiveness. Many technologies show promise, but direct comparisons between NPWT, smart dressings, scaffolds, skin stretching systems, grafts, and flap-based reconstruction remain limited. Predictive algorithms may eventually help match wound type and patient risk profile to the most appropriate closure method.

Future Directions

The future of complex wound closure will likely involve precision wound care. This includes biosensor-guided monitoring, patient-specific biomaterials, artificial intelligence-assisted risk prediction, regenerative scaffolds, topical biologics, closed-loop electrical stimulation, and improved prophylactic strategies for high-risk incisions [22,25].

Important research priorities include identifying which patients benefit most from NPWT, defining the role of smart dressings compared with established therapies, evaluating long-term outcomes of scaffold-based regeneration, and creating validated algorithms that match closure technique to wound characteristics.

Equally important is access. Advanced technologies may improve outcomes but can also increase cost and widen disparities if they are not evaluated for cost-effectiveness and practical implementation.

CONCLUSION

Complex wound closure requires individualized planning based on wound biology, patient risk factors, mechanical tension, infection status, vascularity, and functional goals. Primary closure remains appropriate for selected low-tension wounds, while grafts, flaps, NPWT, skin stretching systems, dermal matrices, scaffolds, and smart dressings expand the options for more difficult defects. Negative pressure wound therapy is one of the most established adjuncts, but it should be used as part of a broader reconstructive strategy. Emerging technologies may transform wound care, yet durable success still depends on foundational surgical principles: adequate

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debridement, vascularized tissue, tension-free closure, dead-space control, infection management, and long-term functional planning.

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