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STRUCTURAL AND FUNCTIONAL ADVANCES IN SURGICAL SUTURE MATERIALS

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Abstract
Recent advances in surgical practice have been closely associated with the development of innovative suture materials exhibiting improved mechanical, biological, and functional properties. Beyond their primary role in tissue approximation, surgical sutures actively interact with the wound microenvironment, influencing inflammatory responses, microbial adhesion, and regenerative processes.
This review focuses on the structural and functional evolution of surgical suture materials, with particular emphasis on filament architecture, degradation mechanisms of absorbable polymers, surface modifications, and emerging smart technologies. Based on current experimental and clinical literature, the properties and performance of monofilament and multifilament sutures, absorbable and non-absorbable materials, as well as antibacterial, drug-eluting, and nanostructured coatings are critically analyzed.
In addition, novel concepts such as stem cell-loaded sutures, electronic and sensor-integrated sutures, and photobiomodulation-assisted modulation of suture–tissue interactions are discussed as promising future directions in surgical biomaterials research. The integration of advanced materials science and biomedical engineering approaches into suture design is expected to enhance wound healing, reduce postoperative complications, and contribute to the development of next-generation multifunctional surgical sutures.
Keywords: surgical suture materials, filament structure, antibacterial coatings, nanotechnology, smart sutures, wound healing.

Introduction

Surgical suture materials represent a critical interface between implanted medical devices and biological tissues and play a pivotal role in determining the outcome of surgical wound healing. Beyond their primary mechanical function of tissue approximation and stabilization, sutures actively interact with the wound microenvironment, influencing cellular behavior, inflammatory responses, microbial adhesion, and the overall dynamics of tissue regeneration [3,14]. The presence of suture material in living tissues inevitably triggers a cascade of biological reactions, including protein adsorption, immune cell recruitment, and fibroblast activation, which collectively shape the reparative process.

In this context, the evolution of surgical suture materials has become an important focus of modern biomaterials science and biomedical engineering. Continuous efforts are directed toward minimizing adverse tissue reactions while preserving adequate mechanical strength and handling properties. To date, more than 250 types of surgical sutures have been introduced into clinical practice, reflecting ongoing attempts to optimize tensile strength, knot security, elasticity, biocompatibility, and resistance to microbial contamination [3–6,16].

While a substantial body of literature is devoted to the clinical selection of sutures based on anatomical location and surgical technique, fewer studies provide an integrated analysis of structural, physicochemical, and technological innovations that define current and emerging trends in suture development. The present review aims to address this gap by focusing on the material-oriented aspects of modern surgical sutures and their implications for biological performance.

Materials and Methods

This article is designed as a narrative review of the literature. The analysis was based on data obtained from domestic and international publications addressing the structural, physicochemical, and functional properties of surgical suture materials. The review included studies focused on filament architecture, degradation mechanisms of absorbable sutures, antibacterial and bioactive surface modifications, as well as emerging technologies such as smart sutures and photobiomodulation-assisted wound management.

Sources were selected from peer-reviewed journals, monographs, conference proceedings, and market reports indexed in international and regional scientific databases. Particular attention was given to publications evaluating the interaction between suture materials and biological tissues, as well as to studies describing innovative material-based approaches aimed at reducing postoperative complications and improving wound healing outcomes.

Results

Filament architecture and mechanical performance

The filament architecture of surgical sutures is a fundamental determinant of both their mechanical behavior and biological performance. Monofilament sutures consist of a single continuous filament and are characterized by a smooth surface morphology, reduced tissue drag, and limited capillarity. These properties contribute to lower bacterial adhesion and reduced inflammatory responses in surrounding tissues, making monofilament sutures particularly advantageous in contaminated or potentially infected surgical fields [3,14].

In contrast, multifilament sutures are composed of multiple twisted or braided filaments, providing superior tensile strength, enhanced flexibility, and improved knot-holding capacity [4,18]. These characteristics are especially valuable in high-tension closures and reconstructive surgery. However, the presence of interfilament spaces facilitates capillary fluid transport and microbial colonization, thereby increasing the risk of inflammatory and infectious complications [14,18].

Degradation mechanisms of absorbable sutures

Absorbable sutures are designed to provide temporary mechanical support to healing tissues and subsequently undergo controlled degradation within the biological environment. Natural absorbable sutures primarily degrade through enzymatic processes, whereas synthetic absorbable materials are predominantly broken down via hydrolytic mechanisms [3–5,14].

The degradation pathway and rate directly influence tensile strength retention and the duration of mechanical support. Premature loss of tensile strength may result in wound dehiscence, whereas prolonged persistence of foreign material may provoke chronic inflammation or fibrotic tissue responses. Recent advances have focused on fine-tuning degradation kinetics through modification of polymer composition, molecular weight,

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crystallinity, and copolymer ratios, enabling predictable and tissue-specific strength loss profiles [20,22].

Functional surface modifications and antibacterial strategies

Surgical site infections remain among the most frequent postoperative complications, accounting for approximately 5% of all surgical interventions worldwide [3,9,11,14]. The implantation of suture material provides an additional surface for microbial adhesion and biofilm formation, highlighting the need for antibacterial strategies.

Triclosan-coated sutures represent one of the most extensively studied approaches and have demonstrated reduced infection rates across multiple surgical disciplines, including cardiac, thoracic, and general surgery [9,12,14,21]. Nanotechnology-based approaches have further expanded antibacterial strategies. Silver nanoparticles exhibit broad-spectrum antimicrobial activity through disruption of bacterial cell membranes, proteins, and DNA [17,21,24]. Incorporation of nanoparticles into the bulk material allows sustained antimicrobial effects while minimizing cytotoxicity [14,17].

Drug-eluting sutures capable of locally delivering anti-inflammatory or antimicrobial agents have also emerged as multifunctional systems that combine mechanical stabilization with targeted pharmacological action [11,12].

Emerging technologies: smart and bioactive sutures

Recent interdisciplinary advances have introduced the concept of smart sutures integrating sensing, monitoring, and therapeutic functions. Electronic sutures incorporating ultrathin silicon sensors or metallic nanomembranes enable real-time monitoring of wound temperature, pH, oxygen tension, and mechanical strain [18].

Parallel experimental research has explored sutures as carriers for bioactive molecules, including growth factors and stem cells, aimed at enhancing local regenerative responses [18,24]. Although technical and regulatory challenges persist, this approach represents a shift toward biologically active wound management systems.

Photobiomodulation and suture–tissue interaction

Photobiomodulation using low-intensity laser or LED irradiation has been shown to modulate inflammatory pathways, improve microcirculation, and stimulate cellular proliferation and tissue repair [2,7,8,23]. When combined with modern suture materials, photobiomodulation may attenuate adverse tissue reactions and promote more favorable wound healing outcomes, particularly in high-risk surgical settings.

Discussion

The analyzed data indicate that modern surgical sutures should be regarded not merely as passive mechanical devices for tissue approximation, but as active participants in the wound healing process. Structural characteristics of sutures, including filament architecture, surface morphology, and material composition, play a decisive role in determining local tissue responses, inflammatory intensity, microbial adhesion, and the dynamics of tissue regeneration. In this context, sutures represent a critical component of the wound microenvironment, capable of modulating both physiological and pathological healing pathways.

One of the key findings emerging from contemporary studies is the close relationship between suture structure and biological performance. Monofilament and multifilament designs exhibit distinct mechanical and biological profiles, influencing not only tensile strength and handling properties but also susceptibility to bacterial colonization and inflammatory reactions. Similarly, the degradation behavior of absorbable sutures has a direct impact on wound stability

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and long-term tissue integration. Improper matching between degradation kinetics and tissue regenerative capacity may result in premature loss of mechanical support or prolonged foreign-body reactions, ultimately compromising surgical outcomes.

The integration of antibacterial coatings, nanostructured materials, and drug-eluting systems reflects a broader shift toward multifunctional biomaterials designed to address multiple clinical challenges simultaneously. Antimicrobial strategies, particularly those based on triclosan or silver nanoparticles, have demonstrated efficacy in reducing surgical site infections; however, their long-term biocompatibility, potential cytotoxicity, and influence on tissue remodeling require careful evaluation. Likewise, drug-eluting sutures offer promising localized therapeutic effects but necessitate precise control of release kinetics and dosage to avoid adverse reactions.

Emerging smart and bioactive suture technologies further expand the functional role of sutures by enabling real-time monitoring of wound conditions and targeted modulation of healing processes. Electronic and sensor-integrated sutures, as well as bioactive carriers for growth factors or cells, illustrate the potential transition toward personalized and adaptive wound management systems. Nevertheless, despite encouraging experimental results, the translation of these innovations into routine clinical practice remains limited by technical complexity, regulatory constraints, cost considerations, and the need for robust long-term clinical data.

Overall, the findings discussed in this review underscore the necessity of a multidisciplinary approach to the development and evaluation of surgical suture materials. Close collaboration between surgeons, materials scientists, and biomedical engineers is essential to balance mechanical performance, biological safety, and functional complexity. Future research should focus not only on technological innovation but also on standardization, comparative clinical trials, and long-term outcome assessment to ensure that next-generation suture materials provide tangible and sustainable benefits in everyday surgical practice.

Conclusion

Advances in materials science and biomedical engineering have fundamentally transformed surgical sutures from passive mechanical tools into multifunctional medical devices capable of actively interacting with the wound microenvironment. Structural optimization of filament architecture, precise control of degradation kinetics, the development of antibacterial and drug-eluting coatings, as well as the integration of smart and bioactive technologies have collectively contributed to significant improvements in surgical reliability, reduction of postoperative complications, and enhancement of patient outcomes [14,18,21].

Modern suture materials not only provide mechanical tissue approximation but also influence inflammatory responses, microbial colonization, and regenerative processes at the surgical site. The ability to tailor suture properties to specific clinical and biological requirements underscores the importance of a multidisciplinary approach to suture design and selection. Emerging strategies, including nanotechnology-based antimicrobial systems, electronic and sensor-integrated sutures, and bioactive carriers for growth factors or cells, highlight the transition toward personalized and function-oriented wound management.

Further progress in this field will depend on close collaboration between surgeons, materials scientists, and biomedical engineers, as well as on rigorous experimental and clinical validation of novel technologies. Such interdisciplinary efforts are essential to ensure the safety, scalability, and clinical applicability of next-generation surgical suture materials and to translate technological innovation into tangible improvements in surgical practice.

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