pISSN 2349-3925 | eISSN 2349-3933

DOI: https://dx.doi.org/10.18203/2349-3933.ijam20243825

Review Article

Seamless innovations: exploring the latest advancements in sutures

Sunil Kumar Venkatappa[1], Vysakh Chandran Nirmala[2], Jaydeep Mondal[3], Ashok Kumar Moharana[4], Venkataraman A. P.[4]*, Cismitha Sharol Pinto[4], Deepak T. S.[4]

[1]Department of Surgery, Bangalore Medical College and Research Institute, Bangalore, Karnataka, India
[2]Department of Surgery, Calicut Medical College, Calicut, India
[3]Department of Surgery, MJN Medical College and Hospital, Coochbehar, India
[4]Clinical Affairs, Healthium Medtech Limited, Bangalore, Karnataka, India

Received: 22 November 2024
Accepted: 12 December 2024

***Correspondence:**
Dr. Venkataraman A. P.,
E-mail: venkataraman.ap@healthiummedtech.com

ABSTRACT

In the realm of surgical medicine, sutures play a pivotal role in the closure of wounds and incisions, serving as a cornerstone technique for promoting efficient healing and minimizing infection risk. The art of suturing demands a surgeon's deft touch and precision, ensuring the seamless union of tissue edges while striving to mitigate the formation of conspicuous scars. Over the years, the landscape of sutures has evolved significantly, witnessing the advent of novel methodologies aimed at enhancing both the efficacy and efficiency of wound closure. This review article delves into these pioneering advancements in sutures that have emerged, ushering in a new era of medical innovation. Among these advancements, modified antimicrobial sutures have emerged as a promising development, arming threads with properties to combat infections at the site of wound closure. Drug-eluting sutures represent another remarkable breakthrough, where medications can be released gradually, offering therapeutic benefits during the healing process. Stem cell-seeded sutures have taken regenerative medicine to a new level, promoting tissue regeneration, and accelerating recovery. In the age of cutting-edge technology, "smart sutures" have become a reality, equipped with sensors and integrated electronics to monitor wound healing in real-time, providing crucial data to healthcare professionals. Surgical zippers offer a unique approach to wound closure, simplifying the process and reducing operating time. Collectively, these novel advancements in sutures demonstrates a remarkable capacity to reduce the incidence of infections, expedite the healing process, and enhance patient outcomes. Moreover, they hold the promise of revolutionizing the field of surgery by rendering procedures less invasive and more effective. However, it is important to note that each suture has its own set of advantages and disadvantages, and the selection of the most suitable suture will be contingent on factors such as the nature and location of the wound, as well as the surgeon's preferences and expertise. As we stand on the precipice of medical innovation, these new sutures underscore the ongoing quest to refine surgical practices and improve patient care, illuminating a path towards a brighter and more advanced future in the field of surgery.

Keywords: Drug-eluting sutures, Incisions, Stem cell-seeded sutures, Suturing, Surgical zippers

INTRODUCTION

Surgical sutures play a crucial role in the field of medicine, serving as indispensable tools that enable the precise union and support of tissues during the intricate process of healing following surgical procedures or traumatic injuries.[1] Surgeons rely on these versatile medical instruments to connect and secure various tissue areas. The need for surgery can arise unexpectedly due to a variety of reasons such as illness, injury, or a medical emergency which are termed as ‘emergency’ procedures. Conversely, in cases where surgical procedures are meticulously planned well in advance, aiming to address pre-identified medical conditions detected through routine health check-ups or diagnostic examinations are termed as ‘elective’ procedures. There are many different types of sutures and suturing techniques that surgeons can use based on the patient needs and the type of surgery being performed.[2] Sutures remain widely used in modern surgical procedures, although alternative approaches like staples, adhesives, and strips exist for wound closure. Over millennia, sutures have evolved, initially crafted from natural fibers like silk, cotton, and catgut, to meet specific surgical needs.[3] As times progressed, technological advancements have given rise to synthetic suture materials crafted from polymers like nylon, polypropylene, and polyester. These synthetic materials offer a plethora of advantages over their natural counterparts. They exhibit superior strength and flexibility, reducing the risk of infection and ensuring more predictable rate of absorption.

The surgical suture sector of the health care industry has grown significantly, with a global surgical suture market size of USD 4.2 billion in 2021.[4] The COVID-19 pandemic's effects have been unprecedented and overwhelming on a worldwide scale, with surgical sutures suffering from a decline in use across all countries. However, as the world moves towards post-pandemic recovery, there is likely to be an increase in the demand for surgical sutures due to the growing prevalence of chronic illnesses and road accidents.[5]

It is also worth noting that while there are other products like surgical staples, glues and strips that can serve as suture substitutes, surgical sutures remain the gold standard for wound closure in many cases. When it comes to managing wounds, these materials can lack the pliability & flexibility provided by sutures. Therefore, despite the availability of alternatives, surgical sutures will continue to be the preferred choice for many surgical procedures due to their effectiveness and reliability. Achieving precise wound management requires the use of sutures that possess suitable mechanical strength and even tension distribution, coupled with exceptional flexibility and pliability, which in turn facilitates decreased complexity during the suturing procedure. However, none of the present commercial sutures can meet all these standards.[3,6]

Therefore, in recent years, there has been a rapid growth in the development of novel sutures that possess improved qualities and desirable features, aimed at enhancing the functional efficacy of sutures.[7] In this review article, we aim to provide an extensive overview of the latest advancements and emerging trends in suture technology. We will delve into the details of modified antimicrobial sutures, drug eluting sutures, stem cell seeded sutures, smart sutures, and surgical zippers, which are designed to enhance precision and efficacy while addressing a range of postoperative wound problems, including surgical site infections, scarring, inflammation, and discomfort. The fields of tissue engineering, regenerative medicine, and minimally invasive surgery all stand to greatly benefit from these innovations.[2,7]

MODIFIED ANTIMICROBIAL SUTURES

Modified antimicrobial sutures are sutures that have been coated or impregnated with an antimicrobial agent to prevent infection at the surgical site.[7] These sutures are commonly used in surgeries where the risk of infection is high, such as in abdominal, orthopaedic, and cardiovascular surgeries. The antimicrobial agents used in modified antimicrobial sutures include triclosan, chlorhexidine, octenidine and silver.[8-10] The antimicrobial coating or impregnation of the sutures can last up to 30 days, providing prolonged protection against infection.[11]

One of the main advantages of using modified antimicrobial sutures is that they can reduce the risk of surgical site infections, which in turn reduces serious complications and reduce prolonged hospital stays. These sutures can also help reduce the need for additional antibiotics and improve patient outcomes.[7]

However, the use of modified antimicrobial sutures should not undermine the importance of good surgical techniques and infection control measures. Adequate instrument sterilization, thorough pre-operative skin preparation, and appropriate antibiotic prophylaxis are still essential in preventing surgical site infections.

SILVER NANOPARTICLES TREATED SUTURES

Silver nanoparticles treated sutures are sutures that have been coated or impregnated with silver nanoparticles. These are composed of clusters of silver atoms varying in size from 1 to 100 nm, have garnered attention as potential antimicrobial agents for use in the field of medicine.[12] Silver nanoparticles have a higher surface area compared to bulk silver, which results in a higher antimicrobial activity.

The use of silver in wound care has been known for centuries due to its antimicrobial properties. Currently, medical devices such as wound dressings for burn injuries and urinary catheters incorporate the use of silver nanoparticles.[12] The antibacterial properties of silver are attributed to its ability to stimulate the production of reactive oxygen species within bacteria, which subsequently disrupts the integrity of microbial DNA and cell membrane.[12,13]

Silver nanoparticle-treated sutures release silver ions into wounds, inhibiting bacterial and microorganism growth, thereby reducing the risk of surgical site infections. A study reported that the application of a silver nanoparticle and hyperbranched polylysine coating on polyglycolic acid sutures led to a notable decrease of 99.5% in the adhesion of S. aureus without inducing cytotoxic effects on fibroblasts, in comparison to uncoated sutures. Additionally, numerous other investigations have demonstrated the antimicrobial properties of silver nanoparticles against *S. aureus* and *E. coli* and have also reported their anti-inflammatory effects.[14]

Similarly, in another study, silver nanoparticles and sodium alginate coated on polyamide sutures showed antibacterial activity.[11] Silver nanoparticles coated on Poly (lactic-co-glycolic acid) revealed antibacterial and anti-inflammatory activity.[15] Furthermore, 0.5% silver nanoparticles coated on silk suture exhibited excellent antibacterial effect and reduced bacterial adhesion against *S. aureus* and *E. coli* without cytotoxic effect on fibroblast.[16]

However, there are also concerns about the potential toxicity of silver nanoparticles, particularly if they are released into the environment. The long-term effects of exposure to silver nanoparticles are not yet fully understood, and more research is needed in this area.[7]

DRUG ELUTING SUTURES

The new era of surgical sutures is represented by drug-eluting sutures that not only serve their mechanical purpose but also release medication in the surrounding area after they are implanted.[17] These drug eluting sutures are coated with a medication to promote healing or reduce the risk of infection after a surgical procedure. These sutures can be made of different materials, such as synthetic polymers or natural materials like collagen, and are coated with a layer of medication that is slowly released into the surrounding tissue over time. These sutures are capable of efficiently delivering drugs, such as antibiotics, anaesthetics, and anti-inflammatory agents, directly into the wound site for optimal efficacy.[2]

Drug eluting sutures also offer wound healing properties in addition to an antimicrobial effect. Therefore, drug eluting sutures represent a potential new generation of treatment for soft tissue repair. There are several methods available for developing drug-eluting sutures, which include coating the surface of the suture using techniques such as dip-coating, grafting, or electrospinning. Manufacturing drug-eluting sutures poses a significant challenge as it involves achieving the desired concentration and efficacy of the drug while preserving the crucial mechanical properties of the suture. This can be accomplished by implementing strategies for controlled drug release and accelerated polymer degradation.[18]

The medication coating on drug-eluting sutures can vary depending on the intended use of the suture. Some drug-eluting sutures are coated with antibiotics to reduce the risk of infection, while others are coated with growth factors to promote tissue regeneration and wound healing. In addition to their therapeutic benefits, drug-eluting sutures can also simplify post-operative care, as they eliminate the need for separate wound dressings or topical medications.[2] These treatments have also allowed surgeons to reduce post-operative complications like surgical site infection, pain, bruising and trauma, and a faster recovery time. Depending on the therapeutic agent utilised, this property can be enhanced. As a result, the need for systemic medications and the possibility of adverse effects from them are decreased.[13]

Following US FDA approval, the modification by coating technique is applied to several different suture materials to avoid the post-operative complications. Triclosan-coated sutures received their first US FDA approval in 2002.[19] These triclosan-coated sutures have been shown to have antimicrobial activity against *S. aureus* and S. epidermidis.[20] Incorporation of antibiotics in various sutures like Tetracycline, Levofloxacin and Vancomycin has demonstrated effective local antimicrobial activity while producing minimal adverse effects. Incorporation of the local anaesthetics like Lidocaine and Bupivacaine into suture has been proven to effectively increase the analgesic action without any adverse reaction. By utilizing drug combinations, the advantages of drug-eluting sutures can be further enhanced. The affected area can experience either synergistic or additive effects when multiple drugs are combined.[13]

Silk sutures coated with Tetracycline hydrochloride and braided silk sutures coated with Levofloxacin hydrochloride both exhibit antimicrobial activity against E. coli [19,21]. Poly (L-lactic acid) and Polyethylene glycol coatings with Levofloxacin inhibit bacterial growth of S. epidermidis [22]. Polypropylene sutures coated with Vancomycin hydrochloride exhibit antimicrobial activity against *S. aureus*, MRSA, and coagulase-negative staphylococci.[22] Poly-e-caprolactone-coated with Lidocaine provide analgesic effects, while Poly (lactic-co-glycolic acid) PLGA-coated with Bupivacaine provide similar effect.[24] Surgical sutures made of Polyvinylidene difluoride and PLGA coated with tacrolimus and ibuprofen exhibit analgesic effects, and polyethyleneamine-coated with dexamethasone exhibit anti-inflammatory properties.[25,26]

This innovative suture offers numerous benefits, such as improved wound healing and tissue regeneration, increased drug loading capacity and sustained drug delivery due to its porous structure, and the release of essential proteins, cytokines, and drugs for managing pain, inflammation, and infections at the wound site. Additionally, its mechanical properties remain uncompromised even after undergoing any modification procedures.[2,27]

Drug-eluting sutures are an emerging technology that has the potential to improve patient outcomes after surgery. Nevertheless, potential complications like excessive scarring, delayed wound healing, and skin reactions necessitate additional research to determine the safety and effectiveness of these sutures across diverse clinical settings.[2]

STEM CELL SEEDED SUTURES

Recent progress in the field of regenerative medicine has enhanced the feasibility of employing cellular therapy as a viable treatment option for numerous diseases. Being able to transport a precise number of cells to a targeted and confined area of interest is crucial for the effectiveness of any cell therapy.[28] Stem cell seeded sutures refer to sutures that are coated with stem cells. These sutures are used in regenerative medicine to enhance tissue repair and regeneration.[13] The stem cells are harvested from the patient's own body or from a donor and then grown in a laboratory. Once the stem cells have reached a sufficient number, they are seeded onto the surface of the sutures. The sutures are then implanted into the patient's body at the site of the injury or surgery. As the tissue starts to heal, the stem cells on the sutures help to promote tissue growth and regeneration.

Upon implantation, these sutures exhibit favourable degradation rate and tensile strength properties that facilitate prompt tissue regeneration. Biodegradable scaffolds are extensively utilized in the field of tissue engineering and regenerative medicine, as they serve as a carrier for the transplantation and differentiation of stem cells into different types of tissues.[7]

Stem cell seeded sutures hold promise for enhancing healing in various medical applications, including wound healing, bone regeneration, and cartilage repair. They have shown promise in animal studies and are currently being evaluated in clinical trials to determine their safety and effectiveness in humans.[2]

The main aim of using stem cells seeded onto sutures is to enhance the concentration of these cells at the site of injury, with the goal of facilitating tissue regeneration and repair processes. While suture-based cell delivery seems like a viable method for transplanting stem cells into soft tissues, it would be difficult to maintain the desired mechanical and physical properties of the sutures used for this approach.[7,29]

There are two major limitations associated with current cell delivery methods, namely low cell engraftment and the lack of targeted cell delivery. To overcome these limitations, a new delivery mechanism using cell-seeded biological sutures has been developed. The use of cell-seeded biological sutures has a wide range of potential applications, particularly in cases where targeted delivery of cells to a specific disease site could help isolate or mitigate the affliction.

For example, using these sutures for wound closures could potentially improve healing time, reduce the inflammatory response, and minimize scar formation. The provisional matrix proteins present in the biological suture could also provide additional structural integrity to the delivered cells for soft tissue repair. Furthermore, the biological sutures could help provide directionality to implanted cells, aligning them parallel to the suture track, which could be crucial in certain applications, such as skeletal muscle, ligament, or nerve repair.[28]

Sutures that incorporate growth factors and/or stem cells have the potential to serve as substitutes for scaffolds in tissue engineering and regenerative medicine. Using sutures as a carrier in cell therapy has resulted in significant clinical benefits, including increased mechanical function of the heart, improved tendon repair, successful tracheal anastomosis, and accelerated wound healing with tissue regeneration in a shorter time frame. Furthermore, the use of such sutures has resulted in significant improvements in repairing strength, resistance to gap formation, and rapid healing, leading to enhanced clinical outcomes in orthopedic injuries. The development of stem cell-modified metallic sutures through nano coatings with shape memory alloy (Nitinol) may also expand the clinical use of such sutures for orthopaedic applications.[7]

One study involves the use of fibrin or a combination of fibrin and collagen microthreads (VitaSutures) with human mesenchymal stem cells (hMSCs) and Quantum dots. This approach resulted in the delivery of hMSCs throughout the thickness of the ventricular myocardium of the heart, with a high cell retention rate (>60%). There was reduction in fibrosis and an increase in the mechanical function of the heart.[30] Another study involved the use of braided Polyblend sutures with pluripotent embryonic cells (Murine), which showed that cells deposited on the repair site were metabolically active and survived in the injured tendon tissue.[31]

Other studies involved the use of braided sutures with poly-L-lysine, which facilitated increased cell adhesion than the fibronectin coated sutures.[32] Polyethylene terephthalate with mesenchymal stem cells enhanced repair strength.[33] Polylactic-co-glycolic acid with adipose-derived stem cells decreased acute inflammatory reaction. Polyglycolic acid sutures with mesenchymal stem cells (porcine and murine), showed abundant deposition of collagen and enhanced wound healing.[34]

SMART SUTURES

An emerging trend in wound closure is the use of programmable or smart sutures. Smart sutures are medical sutures that are equipped with electronic or biochemical sensors and can provide real time feedback on the healing progress of the wound or if there are signs of infection.[35] This information can help surgeons make more informed decisions about patient care, such as whether to administer antibiotics or other treatments.

These sutures contain miniature sensors that can detect temperature changes, pH levels and other indicators of healing process. Smart sutures can also be designed to release drugs or other therapeutic agents to promote healing or prevent infection.[13] They may be made from biodegradable materials that dissolve over time, reducing the need for additional surgeries to remove the sutures.[7] There are 3 different types of smart sutures.

Shape memory

These sutures are the type of surgical sutures, made from a special type of shape memory polymer that are designed to have shape memory properties. This means that the suture can be bent or deformed during surgical procedure (temporary state), and then return to its original state after application of thermal heat.[36] This can be useful in a variety of surgical applications, such as in the closure of wounds or in the fixation of tissues or organs.

These sutures are designed to induce self-tightening knots when exposed to thermal heat, making it easier for surgeons to close wounds, especially in confined spaces such as deep wounds or during minimally invasive surgery. This reduces the complexity of knot tying and can potentially improve the precision and speed of wound closure.[13,36]

In addition to their use in wound closure, programmable or smart sutures can also be designed to incorporate antimicrobials and stem cells for biomedical and regenerative medicine applications. Barbed sutures, either throughout the entire suture or in specific sections such as the barbs or suture body, can be produced from shape memory polymers to enhance tissue adherence and achieve favorable clinical outcomes.[7]

Despite the significant progress made in the field of medical sutures with the use of shape memory polymers, there are still some challenges associated with their use. For example, this technology requires thermal heating at the suturing site, which may not be practical in all surgical settings. Additionally, the higher cost of these sutures compared to traditional ones necessitates further research and development to fully grasp their potential and optimize their utilization for enhancing surgical outcomes.[3]

Elastic sutures

These are a type of surgical suture that are made from thermoplastic polyurethane. These sutures offer a high level of mechanical strength and significant elasticity, allowing them to withstand tension and deformation.[37] They are typically used to close incisions or wounds and can be helpful in reducing tension on the wound edges and promoting faster healing.

The tensile properties of these sutures make them a feasible and safe option for closing midline laparotomy wounds, with promising results in preventing postoperative complications such as burst abdomen following abdominal surgery. In an in vitro study, the elastic suture material demonstrated a significant reduction in the number of inflammatory cells and promoted better wound healing compared to polypropylene sutures in rabbits after 21 days of implantation.[37]

Elastic sutures require further studies to address the potential complications of suture pull through and wound dehiscence. Additionally, they may not be appropriate for use in all types of surgical procedures, and the choice of suture material will depend on number of factors, including the locations of incision, patient’s medical history and the surgeon’s preferences.[13]

Electronic sutures

These are a type of filament actuator or sensors. These sutures have the ability to monitor the healing process of a wound, as well as provide feedback to the surgeon regarding the wound status. The electronic sutures are flexible and easy to thread through surgical needles, and they have a strong pull strength. They can measure temperature accurately, which can help detect infections and maintain optimal temperature for healing at the wound site.[7]

While there have been many potential markers for wound healing, currently only a few, including pH, oxygen, uric acid, haemoglobin, infection, and protease activity, are being used for sensor application to monitor and manage wound sites.[38,39] Moreover, incorporating force sensors with feedback control in sutures can help to determine the threshold of tension during suturing of different tissues, enabling control and modulation of high or low tensions in sutures at wound closure sites. This can reduce the negative effects of disproportionate tension on wound healing.

As minimally invasive surgery and suture technology continue to progress, electronic sutures with integrated sensors for monitoring wound pH, exudates, bacteria, oxygen, and enzymes, as well as a temperature monitoring system, can enhance the accuracy of wound monitoring and improve healing outcomes for both acute and chronic wounds.

According to Kim et al, a smart electronic suture has been developed with ultrathin and flexible silicon sensors integrated onto polymer or silk strips for monitoring wounds. The suture material was designed with a serpentine shape, and it includes two temperature sensors made of silicone and platinum nano membrane, as well as a microheater made of gold, which helps in monitoring wound temperature and supports the healing process.[40]

Electronic sutures are still in early stages of development, and more research is needed to fully understand their potential applications and limitations. However, they represent an exciting new development in the field of surgical technology and could eventually lead to improved outcomes for patients undergoing surgical procedures.[7,41]

Overall, smart sutures represent an exciting development in the field of surgery and wound care, offering the potential to improve patient outcomes by providing more personalized and effective treatments.

SURGICAL ZIPPER

The surgical zipper technique, a novel non-invasive method for closing skin incisions, has gained significant popularity for its ability to promote effective wound healing.[13] The surgical zipper is a non-invasive method of closing skin incisions that is both sterile and adjustable.[13] It is a hydrocolloid adhesive-based solution that can replace traditional staples and sutures for closing the top layer of skin. The zipper can be applied directly to the unbroken skin on either side of the incision, exerting a consistent force along the edges of the wound.[42] Surgical zippers are designed for early incision inspection just by opening it and then closing it. They allow surgeons to access a specific area of the body quickly and easily without compromising the sterile environment.

The surgical zipper is useful for closing straight or slightly curved incisions, with an application that should be 2-4 cm longer than the wound itself, and a distance of 0.5 cm between the zipper teeth and the edge of the incision. To ensure proper closure, the operator should manually elongate the incision to bring the wound edges together and then gently pull on the rear loop while closing the zipper. The surgical zipper is available in various sizes, ranging from 6 to 50 cm, and can effectively close wounds that are 4 to 47 cm in length.[43]

Surgical zippers are a valuable tool in various medical procedures, offering patients comfort and reducing the risk of surgical site infections. They are a safe and easily manageable device, significantly shortening wound closure time and improve the overall cosmetic outcome. Orthopaedic surgeries that require extensive incisions to access bones & joints, and cardiac surgeries that necessitate prolonged access to the heart are common applications for surgical zippers.[42] Additionally, they are particularly useful in paediatric and young patients, as well as in oncology patients undergoing combined treatments for neoplastic disease.[13]

While zippers may offer benefits such as anti-infective properties, time efficiency, and improved cosmetic outcomes when used for wound closure, it is important to note that they are not universally applicable and should not be viewed as a replacement for meticulous surgical technique and sterile practices.[42] Zippers may not be suitable for wounds under high tension, wet or curved wounds exceeding 20 degrees, or in obese (overweight) patients, and there is no evidence to suggest that they can significantly reduce the occurrence of wound dehiscence or overall wound complications.[13,42] Further research is necessary to establish the validity and consistency of these findings.

CONCLUSION

In conclusion, the evolution of sutures from ancient methods using fibres to modern innovations underscores the crucial role they play in promoting healing and facilitating wound closure. With the global rise in surgical procedures, the demand for advanced sutures rises, necessitating ongoing technological advancement. The relationship between technological advances and complex surgical procedures is interdependent and mutually beneficial. Developments in suture technology holds immense promise for improving patient outcomes and minimizing complications across various clinical, surgical, and wound management applications. However, it is important to note that despite significant progress, only modified antimicrobial sutures (triclosan-coated sutures) have gained widespread usage, while other techniques remain in the research phase and are not yet available widely in the market. This highlights the imperative for further exploration and development in suture technology to address emerging challenges and meet evolving patient and healthcare provider needs. Collaborative efforts between researchers, clinicians, and industry stakeholders will be essential in realizing the full potential of suture technology and ensuring its widespread adoption in clinical practice.

Funding: No funding sources
Conflict of interest: None declared
Ethical approval: Not required

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Cite this article as: Venkatappa SK, Nirmala VC, Mondal J, Moharana AK, Venkataraman AP, Pinto CS. Seamless innovations: exploring the latest advancements in sutures. Int J Adv Med 2025;12:147-54.