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Common Trends in Hernia Repair: Meshes-An Updated Review of Novel Trends

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Abstract:

Background: Abdominal wall hernias are a common condition that can lead to significant morbidity and functional impairment. Affecting millions worldwide, hernias are often treated surgically. Over the past six decades, hernia repair techniques have evolved, with surgical meshes becoming the standard treatment. Despite advancements, there is no universally accepted "gold standard" for hernia repair, and ongoing research focuses on improving the materials and designs of meshes.

Aim: This review aims to provide a comprehensive update on the current trends in hernia repair, with a focus on the different types of meshes available, their properties, and advancements in material science that improve clinical outcomes.

Methods: The review analyzes a wide range of literature, including clinical studies and innovations in hernia repair, with special attention to recent developments in mesh technologies. The meshes are categorized into synthetic, biological, and composite types, highlighting the latest advancements in lightweight materials, antimicrobial coatings, and hybrid constructions.

Results: Recent developments have introduced meshes that offer enhanced adhesive qualities, antimicrobial features, and better integration into the abdominal wall. Lightweight meshes and composite materials have improved the biological response, reducing the risk of infection and complications. The study also highlights ongoing clinical trials exploring new mesh configurations and materials. While synthetic meshes remain the most common, biological and composite meshes are becoming important alternatives in specific cases.

Conclusion: Hernia repair continues to benefit from advancements in mesh technology, with promising improvements in mesh integration, biocompatibility, and patient outcomes. The field is evolving towards more personalized approaches, including the use of hybrid and composite meshes tailored to patient needs. Continued research is crucial for refining mesh materials and techniques, ensuring better clinical outcomes, and reducing complications.

Keywords: Hernia repair, meshes, synthetic meshes, biological meshes, composite meshes, abdominal wall hernias, surgical materials, biocompatibility, clinical trials, mesh technologies.

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Introduction:

With layers of muscle, subcutaneous adipose tissue, skin, preperitoneal fascia, and peritoneum, the human abdominal wall is a complex, stratified anatomical structure. In order to maintain postural support, control abdominal pressure, and contain and protect the intra-abdominal contents, these structures attach to and connect to the skeletal framework. However, what are commonly called "hernias" are flaws in the abdominal wall that allow the protrusion of abdominal contents [1, 2, 3]. Hernias of the abdominal wall are common clinical conditions that greatly increase morbidity and functional impairment [4]. Over 20 million hernia repairs are made worldwide each year, making it the second most prevalent reason for consultations with general surgeons across a range of age groups and the third most common abdominal pathology [2, 5]. Many hernias are detected in advanced stages, and public awareness of the condition is still lacking despite its high frequency. To reduce the chance of serious consequences, prompt surgical intervention is crucial [6,7]. Despite its effectiveness, hernia repair presents many difficulties and usually requires surgery [6,8]. Although there have been significant advancements in hernia repair methods over the last 60 years, there is currently no accepted gold standard for the treatment of abdominal wall hernias. The best method for regaining the musculofascial layers' structural and functional integrity is still using surgical meshes [1, 8]. A variety of mesh materials are available to modern doctors, each with unique benefits and drawbacks [9]. Yet, the perfect mesh design that strikes the best possible balance between affordability, surgical handling, biocompatibility, and usefulness has not yet been created [10]. In order to attain better therapeutic results, current research is mostly concentrated on improving the polymer architecture and integration features of these medical fabrics [8].

The pathophysiology and repair of abdominal hernias are tackled holistically in this article. An introduction to the disease and general treatment approaches is given first, then an assessment of the many abdominal meshes that are available and a thorough discussion of cutting-edge scaffolds made specifically for hernia repair. Innovations in lightweight materials, meshes with improved adhesive qualities, antimicrobial textiles, composite and hybrid constructions, and new mesh configurations are given special attention. The review also offers thorough insights into current clinical trials in this field. Although mesh products have been the subject of several previous reviews [1,11–15], this work attempts to provide a fresh viewpoint by bringing the literature up to date with the most recent advancements. The study hopes to act as a fundamental resource for upcoming studies and advancements in hernia repair techniques by providing a thorough examination of current approaches.

Abdominal Wall Hernia Pathology and Treatment Approaches

The abnormal protrusion of an organ or tissue through a weak or damaged abdominal wall is known as a hernia. This disorder develops when anatomical flaws, loss of intra-abdominal pressure, or weak abdominal muscles undermine structural integrity [1, 2, 5, 16]. Age, gender, genetic susceptibility, anatomical variances, obesity, smoking, trauma, recurrent heavy lifting, pregnancy, and complications from prior surgery are some of the contributing variables [1,13,16]. In addition to irregular growth factor activity, dietary deficiencies, and changed cellular phenotypes, hernia formation is molecularly linked to anomalies in extracellular matrix (ECM) metabolism, specifically collagen synthesis. Even though our knowledge of these mechanisms has advanced significantly, further investigation is still needed to pinpoint the precise connections and gene expressions that contribute to the development of hernias [1]. Groin hernias and ventral hernias are the two main categories into which the World Society of Emergency Surgery (WSES) divides abdominal wall hernias according to their anatomical location. The lower abdomen is the site of groin hernias, which include femoral, direct, and indirect inguinal hernias. On the other hand, umbilical, epigastric, Spigelian, lumbar, and incisional hernias are all included in the category of ventral hernias [13,17]. Localized pain, decreased mobility, and severe restrictions in day-to-day activities can all result from hernias. In addition, they can compromise function, compress intra-abdominal fluids, distort the shape of the abdomen, and lower the general quality of life for those who are impacted [5,13,16,18]. To preserve the integrity of the abdominal wall and avoid complications, early detection and management are essential.

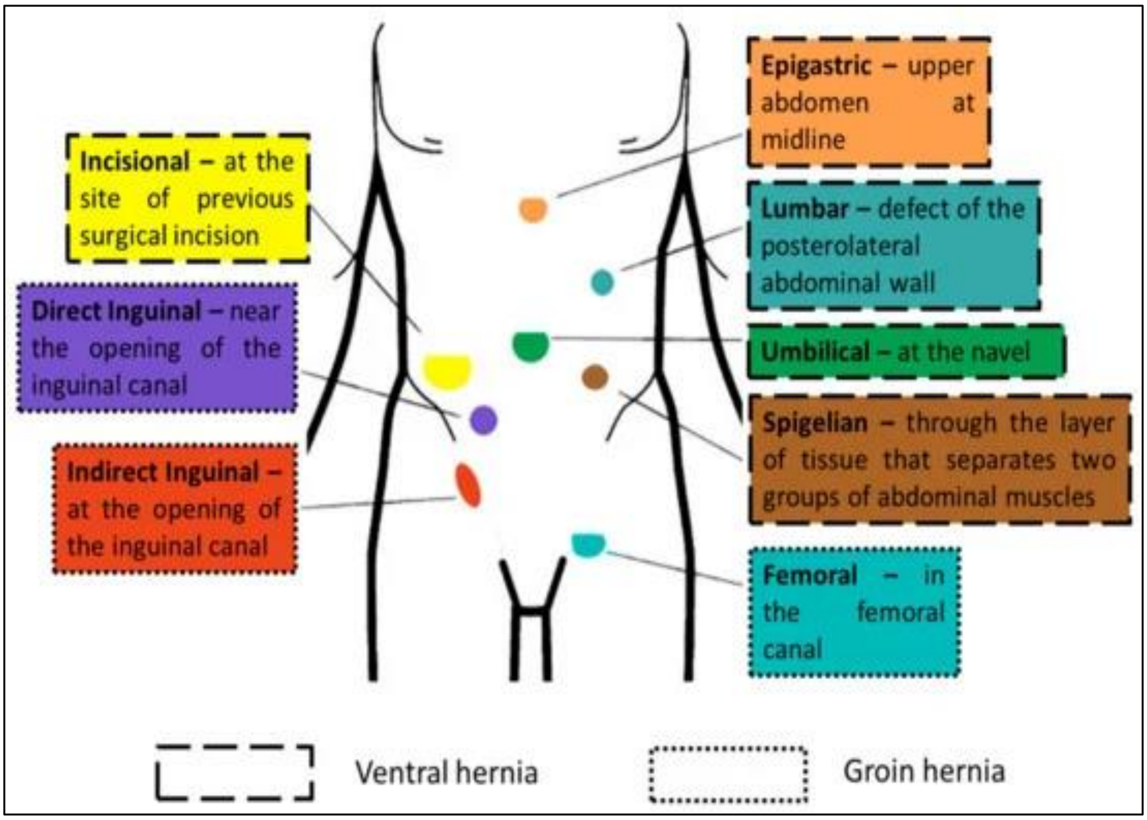

Figure 1: Location of Different Types of Abdominal Hernia.

The size and severity of the hernia determine the therapeutic approach to be used. A cautious waiting strategy might be suitable in non-life-threatening situations, enabling ongoing condition monitoring. However, surgical correction is usually required for serious hernias. The most common approach is open repair surgery, such as the Lichtenstein operation, in which an incision above the hernia site is used to close the defect using a variety of fastening techniques. Laparoscopic surgery is frequently used to treat recurrent hernias because it provides a less invasive option. Both methods work for all kinds of hernias, and the surgeon's skill level and the patient's preferences will determine which is used. Although they require general anesthesia, laparoscopic surgeries are linked to shorter hospital stays and less postoperative pain. On the other hand, whereas open repairs are easier to execute and require local anesthesia, they come with a higher risk of infection and longer hospital stays [13,19–21]. A significant advancement in hernia repair occurred with the introduction of surgical meshes in the 1950s. Before this invention, sutures consisting of silk, silver, or polymers were used to close hernias. These sutures had a high recurrence rate and were linked to problems like ischemia and rupture [1,4]. The introduction of polyethylene mesh in 1958 transformed the industry and made it possible to create a wide range of mesh products [8]. In order to lower the risk of recurrence, mesh implantation is now a common procedure in hernia surgery, offering mechanical support and encouraging tissue integration [4,22]. The mesh's positioning has a big impact on the immunological response, tensile strength, and integration process. Onlay, inlay, sublay-retromuscular, sublay-preperitoneal, and sublay-intraperitoneal sites are common anatomical locations for mesh installation. Clinicians continue to disagree over the best placement approach, which emphasizes the need for more research and standardization in hernia repair procedures.

Currently Available Abdominal Meshes

The repair of hernias has significantly benefited from advances across multiple disciplines, particularly through the development of bioprosthetic devices, innovative materials, advanced surgical techniques, and integrated methodologies [24]. Among the various options for hernia repair, biomedical textiles provide a diverse array of clinically available meshes, each offering distinct advantages and limitations based on their application and placement [9]. The following sections provide a detailed overview of the different types of meshes currently utilized in hernia repair, categorized into synthetic, biological, and composite meshes based on their constituent materials.

Synthetic Meshes

Synthetic meshes are widely regarded as the preferred option for repairing abdominal wall defects due to their proven clinical effectiveness over extended periods of use [16,25]. These polymer-based meshes are valued for their desirable mechanical properties, including elasticity and tensile strength, which allow them to effectively withstand intrabdominal wall pressures and minimize the risk of re-herniation. The porous structures of these textiles, knitted from polymer fibers, also contribute to their cost-effectiveness, making them a popular choice for hernia repair [4,16,25]. Synthetic meshes are classified into two main categories based on their polymer composition: permanent (non-resorbable) and absorbable (resorbable) [16,26].

1. **Non-Resorbable Meshes**: Non-resorbable meshes are durable materials that maintain their structural integrity indefinitely within the body. Commonly used in hernia repairs, these meshes are primarily made from polypropylene, polyester, polytetrafluoroethylene (PTFE), and expanded PTFE. Additionally, materials such as polyvinylidene fluoride and polyurethane are viable options for manufacturing these meshes [16,22].
2. **Resorbable Meshes**: Resorbable meshes, in contrast, are composed of biodegradable materials that degrade over a specified period. The degradation timeline can range from short-term (days to weeks), mid-term (weeks to months), to long-term (months to years), depending on the requirements of the wound. These meshes are typically fabricated from biodegradable polymers such as poly-4-hydroxybutyrate, polyglactin, polylactic acid, polyglycolic acid, polycaprolactone, and polyvinyl alcohol [16].

However, resorbable materials may degrade prematurely, potentially compromising tissue integrity during cellular remodeling processes [25]. Conversely, non-resorbable polymers have been associated with a higher incidence of foreign body reactions and adhesion formation. Consequently, a hybrid approach combining absorbable and non-absorbable polymers has been explored for the development of next-generation meshes [22]. While synthetic meshes are extensively used in clinical practice, they are not universally suitable for all scenarios. For instance, synthetic meshes are contraindicated in cases involving open abdomen repairs or contaminated and infected fields due to the heightened risks of adhesion, chronic sepsis, erosion, and enteric fistula formation [25]. Permanent polymeric meshes are also susceptible to postoperative infectious complications, which may necessitate their removal [26]. Synthetic meshes are commercially available under various trade names and are manufactured by leading biomedical companies. The following are examples of commonly used synthetic meshes:

- **Polypropylene**: Prolene (Boston Scientific, Marlborough, MA, USA), Marlex (Bard Davol, Warwick, RI, USA), Parietene (Covidien-Medtronic, Fridley, MN, USA), Surgipro (Covidien-Medtronic), and ProLite (Pierson Surgical, North Bradley, Trowbridge, UK).

- **Polyethylene Terephthalate Polyester**: Dacron (DuPont, Wilmington, DE, USA) and Mersilene (Ethicon, Johnson & Johnson, Bridgewater, NJ, USA).
- **Polytetrafluoroethylene (PTFE)**: Teflon (DuPont).
- **Expanded Polytetrafluoroethylene (ePTFE)**: Gore-Tex (W.L. Gore and Associates, Newark, DE, USA).
- **Polyglycolic Acid**: Dexon (American Cyanamid, Bridgewater, NJ, USA).
- **Poly-4-Hydroxybutyrate**: Phasix (Bard Davol).
- **Bioengineered Silk**: Seri (Sofregen Medical, Framingham, MA, USA).

Biological Meshes

Biological meshes serve as a viable substitute for synthetic counterparts, particularly in infected environments encountered during complex abdominal wall hernia repairs [4,25]. These biomaterials are associated with reduced inflammatory responses and enhanced biocompatibility, making them highly suitable for patients categorized as high-risk [4]. Derived from either human (allograft) or animal (xenograft) sources, biological meshes are primarily composed of the extracellular matrix (ECM). The ECM, enriched with collagen I and signaling molecules, is fundamental to these meshes' structural, mechanical, and biochemical properties. It facilitates an environment conducive to wound healing and tissue regeneration by promoting neovascularization and native fibroblast infiltration [4,25,26,29]. The preparation of biological meshes involves the use of human dermis, porcine small intestine submucosa, porcine dermis, bovine dermis, and bovine pericardium. These tissues are processed to remove cellular and DNA components, resulting in immunologically inert matrices. To further enhance durability, the scaffolds may undergo crosslinking to inhibit collagenase activity, preserving their structural integrity and extending their incorporation period within surrounding tissues [26]. Despite their advantages, the cost of biological meshes is significantly high, restricting their use in straightforward, uncontaminated hernia repairs. Additionally, they are susceptible to gradual stretching over time due to the retention of elastin proteins [4,25]. Nevertheless, in situations where their use is justified, various biological meshes derived from human, porcine, and bovine sources are commercially available. For instance, human dermis meshes include Alloderm (LifeCell), Allomax (Bard Davol), and Flex HD (Ethicon). Porcine dermis meshes are represented by products such as Strattice (LifeCell), Permacol (Covidien-Medtronic), and Cellis (Meccellis Biotech). Porcine intestine-derived meshes include FortaGen (Organogenesis) and Biodesign/Surgisis (Cook Medical). Furthermore, bovine dermis and pericardium scaffolds, such as SurgiMend (TEI Biosciences) and Veritas (Baxter), respectively, provide additional options for clinical application.

Composite Meshes

Composite meshes have been developed for hernia repair as a means of addressing the limitations associated with single-material scaffolds. By combining the advantages of two synthetic materials or blending a synthetic with a natural material, composite meshes achieve improved integration within host tissue while ensuring effective mesothelialization at the peritoneal level. This approach helps mitigate complications associated with reticular materials, such as adhesions, mesh migration, and intestinal fistula formation [5]. These meshes retain the mechanical properties of conventional non-absorbable polymers like polypropylene and polyethylene terephthalate but reduce their associated risks through the incorporation of an absorbable netting layer [1]. Another innovative design involves meshes with a synthetic layer positioned towards the dermis to provide mechanical strength and stimulate collagen deposition, while a naturally degradable biomaterial layer faces the peritoneum to prevent visceral adhesion [17]. Given these advantageous features, several composite mesh products have become commercially available. For instance, *Gore Bio-A* by W.L. Gore and Associates is made of polyglycolic acid reinforced with trimethylene carbonate [30]. The *Tigr Matrix* by Novus Scientific consists of knitted fibers composed of a copolymer of glycolide, lactide, and trimethylene carbonate, along with a copolymer of lactide and trimethylene carbonate [31]. Medtronic offers *Parietex,* a 3D monofilament polyester textile with a hydrophilic absorbable collagen film [32], and *Parietene,* which features transparent macroporous polypropylene on one side and an absorbable collagen film on the other side [33]. Additional examples include *Sepramesh* by Bard Davol, comprising polypropylene mesh with a hydrogel safety coating [34], and *Composix,* a polypropylene mesh combined with a submicronic ePTFE barrier [35]. *DynaMesh-IPOM,* produced by DynaMesh, utilizes a dual-component structure primarily composed of high-purity polyvinylidene fluoride with a smaller proportion of polypropylene [36]. Ethicon, a subsidiary of Johnson & Johnson, manufactures *Proceed,* which incorporates polypropylene mesh layered with oxidized regenerated cellulose and polydioxanone suture polymer film [37], and *Vicryl,* a polypropylene-polyglactin 910 absorbable woven/knitted composite mesh [38]. Lastly, Medtronic also offers *ProGrip,* a macroporous, monofilament polyester or polypropylene mesh that integrates thousands of poly-lactic acid resorbable microgrips [39].

Limitations of Currently Used Meshes

The use of meshes in hernia repair has introduced numerous challenges for clinicians due to the increasing prevalence of novel non-infectious and infectious complications. Post-implantation issues include inflammation, impaired wound healing, postoperative and chronic pain, seromas, adhesions, mesh migration, and implant rejection [13,22,40]. Additional complications, such as fibrosis and calcification, may arise from the selection of inappropriate mesh materials [22]. While meshes are not strongly associated with high surgical site infection rates, they are nonetheless recognized by the host body as foreign objects, which can provoke inflammatory responses. If an infection does occur in the vicinity of the implant, it may exacerbate abdominal wall damage, intensify postsurgical pain, and increase the risk of recurrence [40]. The likelihood of infection is also influenced by patient-specific factors such as diabetes, immunosuppression, obesity, and smoking habits, necessitating particular care in the selection of suitable meshes for these populations [22]. To summarize, synthetic meshes offer good mechanical strength and are cost-effective but are associated with significant drawbacks, including inflammation, stiffness, pain, a high rate of infections, and the formation of fistulae. Biologic meshes, while less prone to inflammation and fistula formation and associated with reduced fibrosis, are more expensive and provide lower mechanical strength. Composite meshes demonstrate reduced fistula formation but can still induce varying degrees of inflammation. These considerations underline the complexity of selecting an appropriate mesh type tailored to individual patient needs and clinical scenarios.

Emerging Solutions for Performant Abdominal Meshes

Despite the extensive array of currently available abdominal meshes, there remains significant potential for further advancements in optimizing hernia repair management. Each type of material currently in use presents inherent limitations, prompting researchers to pursue the development of an "ideal mesh" that would meet stringent criteria related to biocompatibility, infection resistance, ease of handling, durability, and cost-effectiveness. Although no such ideal mesh has been developed yet, studies have demonstrated that achieving this goal depends on factors such as material choice, design, insertion techniques, and positioning relative to the abdominal wall. An ideal mesh would be constructed from a durable, biologically inert, non-carcinogenic, and infection-resistant material that induces minimal foreign body reactions and avoids pathological fibrosis [8,10,28]. The mechanical and biological attributes of meshes are also influenced by their textile type (woven or knitted), fiber configuration (monofilament or multifilament), and pore size [22]. Pore size, in particular, plays a critical role in aspects such as adhesion risk, tissue integration, active surface area, elasticity, and material memory [8]. Moreover, the ideal mesh should facilitate remodeling or regeneration of tissue resembling native fascia, potentially through the incorporation of polymeric scaffolds embedded with signaling molecules that stimulate immune cells and fibroblasts for tissue regeneration [4]. Although an ideal mesh remains elusive, several promising research avenues have emerged. These include the development of lightweight materials, innovations in mesh attachment mechanisms, the creation of antimicrobial implantable textiles, the formulation of advanced composite and hybrid materials, and novel mesh designs. These advancements are discussed in detail below.

Lightweight Materials

Lightweight meshes (LWM), characterized by larger pore sizes and reduced material surface areas, have gained attention for their potential to diminish foreign body reactions and fibrosis. Compared to heavyweight meshes (HWM), LWM are more flexible, exhibit superior physical properties, and support better postoperative activity profiles [8]. Research has consistently highlighted their benefits. For instance, Sidharta et al. [6] found that elderly men undergoing herniorrhaphy with the Lichtenstein technique experienced reduced postoperative pain with LWM compared to HWM. Similarly, Lata et al. [41] reported that patients treated with HWM were more likely to experience chronic pain, foreign body sensations, and stiffness at the incision site compared to those receiving LWM. These advantages also extended to early mobility and faster returns to daily activities for patients treated with LWM. Additional studies reinforce these findings. Ahmed Abd El A et al. [42] demonstrated reduced postoperative pain and earlier resumption of routine activities with LWM used in laparoscopic transabdominal preperitoneal repair of inguinal hernias. However, longer operative times were noted, with no significant differences observed in chronic pain, postoperative complications, or recurrence rates after six months. Similarly, RezK et al. [43] compared LWM and HWM for ventral hernia repair and found that LWM were associated with reduced chronic pain, fewer complications (e.g., seroma and infection), and lower recurrence rates. Nonetheless, the higher costs of LWM remain a significant barrier, warranting further investigation through long-term studies with larger patient cohorts to establish their sustained efficacy and cost-effectiveness.

Materials with Improved Attachment

Current meshes frequently encounter challenges related to adhesion and chronic pain. Enhancing mesh attachment to the abdominal wall could mitigate these issues, streamline implantation, and reduce operative times [8,44]. One approach to achieving this involves the development of self-fixation textiles that anchor themselves using grips or adhesives, thereby eliminating the need for sutures or tacks, which can cause unnecessary trauma [5]. For example, Ben Yehuda et al. [45] introduced a bio-adhesive-based self-fixation mesh (LifeMesh™) as an alternative to conventional tack fixation. In animal studies, LifeMesh demonstrated excellent incorporation into the abdominal wall, strong fixation, and minimal adhesion after bio-adhesive degradation within 28 days. Similarly, Harman et al. [46] developed a bio-adhesive-polypropylene mesh system incorporating a bifunctional poloxamine hydrogel adhesive and a poly-glycidyl methacrylate (PGMA) layer grafted with human serum albumin. Their findings revealed significantly improved adhesive strength and satisfactory tissue integration within 42 days of implantation in a rabbit model. Another innovative approach to improving mesh attachment involves the incorporation of cellular components into the textile structure. Dong et al. [47] created a composite electrospun scaffold using a thermoresponsive hydrogel and biodegradable polymer seeded with rat adipose-derived stem cells. This configuration provided a biocompatible, three-dimensional fibrous matrix with enhanced mechanical strength, facilitating cell adhesion, defect repair, regeneration, and vascularization. In a related study, Lesage et al. [48] seeded mesenchymal stem cells derived from amniotic fluid onto electrospun polylactic acid scaffolds. These polymeric matrices supported cell adherence and proliferation, and, after 14 days, the meshes were well-penetrated by inflammatory cells, new blood vessels, and collagen fibers. Implantation in rat models demonstrated that stem cell integration effectively modulated the host response, with macrophage profiles similar to controls. These advancements highlight significant progress toward improving mesh attachment, ensuring better clinical outcomes, and reducing complications in hernia repair applications.

Antimicrobial Materials

To mitigate infection risks associated with abdominal hernia repair, antimicrobial meshes have emerged as a significant innovation. These meshes achieve antimicrobial efficacy through two principal strategies: integrating an additional layer that gradually releases an antimicrobial agent or embedding antimicrobial compounds within the existing mesh structure. These approaches aim to inhibit bacterial adhesion and colonization, thereby reducing postoperative infection rates [22,49,50]. Recent advancements have introduced various antimicrobial meshes with promising results. Dydak et al. [51] incorporated a bacterial cellulose layer infused with the antibiotic gentamicin onto polypropylene-based meshes. This modification demonstrated superior bacterial growth inhibition compared to uncoated meshes, while maintaining high biocompatibility with fibroblast cells. Similarly, Pérez-Köhler et al. [52] applied a carboxymethylcellulose gel containing rifampicin to synthetic polypropylene meshes. In preclinical models involving *Staphylococcus aureus* and *S. epidermidis* infections in rabbits, these coated meshes achieved complete bacterial clearance and exhibited optimal tissue integration without detectable systemic antibiotic levels. Additionally, the same research group [53] explored a thermo-responsive hydrogel formulation loaded with rifampicin. This hydrogel transitions to a biodegradable gel upon reaching body temperature, enabling effective coating of the mesh and adjacent tissues. The hydrogel provided sustained antibacterial activity for five days without cytotoxic effects, highlighting its potential as a complementary tool for infection prevention and enhanced tissue integration. Nanotechnology has further advanced antimicrobial applications by leveraging the unique properties of nano-sized materials to combat infections [49,54–58]. Notably, Afewerki et al. [59] engineered multifunctional bactericidal nanofibers using a blend of polycaprolactone methacrylated nanofibers and gelatin methacryloyl. These fibers exhibited bactericidal activity, low inflammatory responses, tunable mechanical properties, and excellent hydrophilicity, making them suitable for abdominal meshes that support biointegration and tissue ingrowth. Similarly, Liu et al. [60] developed a polycaprolactone/silk fibroin mesh incorporating amoxicillin-loaded multi-walled carbon nanotubes. This nanofibrous design demonstrated biocompatibility, mechanical robustness akin to the abdominal wall, and sustained antibiotic release, effectively inhibiting *E. coli* growth. The incorporation of antimicrobial nanoparticles, such as silver, gold, copper, and zinc oxide, offers another promising avenue for infection-resistant meshes [49,55,56,61,62]. Metal-based nanoparticles have shown efficacy against various pathogens, including antibiotic-resistant strains, and have been actively investigated for developing antimicrobial scaffolds for hernia repair [63–67].

Other Innovative Materials

In pursuit of superior alternatives to traditional abdominal meshes, research has focused on composite and hybrid materials with unique physicomechanical and biological properties. Li et al. [68] developed a mesh combining poly (l-lactide-co-caprolactone) with porcine fibrinogen. The optimal formulation, with a 4:1 ratio of synthetic to biological material, demonstrated desirable mechanical strength, shrinkage rate, porosity, and hydrophilicity. These features facilitated a balance between material degradation and host tissue growth, promoting effective tissue remodeling. Mori da Cunha et al. [69] introduced a hydrogen-bonded supramolecular polymer made of ureidopyrimidinone moieties within a polycarbonate base. Although this composite performed marginally better than standard polypropylene meshes, additional optimization is required for clinical application. Alternatively, Liu et al. [70] designed a hybrid material integrating polycaprolactone, silk fibroin, and decellularized human amniotic membrane. This innovative mesh provided a conducive microenvironment for cell proliferation and neovascularization while minimizing inflammatory and foreign body responses.

Further advancements include polycaprolactone-containing composites for abdominal wall repair. Liu et al. [71] fabricated a double-layer nanofiber membrane combining polycaprolactone, graphene oxide, and chitosan, enhanced with N-acetylcysteine. This material demonstrated excellent mechanical strength, biocompatibility, and anti-adhesion properties, making it a strong candidate for hernia repair. Chalony et al. [72] developed a non-woven material using poly (ethyl-2) cyanoacrylate reinforced with polyurethane. This composite showed suitable mechanical properties for intraperitoneal hernia mesh implants, ensuring biocompatibility. Another innovative material by Wang et al. [73] involved a poly-L-lactic acid scaffold grafted with basic fibroblast growth factor (bFGF). This design enhanced hydrophilicity, sustained bFGF release, and regulated immune cytokines, reducing inflammation and promoting collagen deposition. Zhou et al. [74] explored a core-shell electrospun fibrous membrane with puerarin in the core and an RGD-modified shell. The puerarin core inhibited endogenous inflammation, while the RGD shell promoted cell viability, biocompatibility, and exogenous inflammation suppression. Testing in rat models demonstrated promising wound healing properties, including enhanced collagen deposition, smooth muscle formation, and vascularization.

Novel Mesh Designs

In addition to the selection of fabrication materials, the design of the mesh itself plays a pivotal role in the success of hernia repair. The architectural configuration and shape of the reinforcement textiles significantly influence clinical outcomes. A notable contribution to this field is the study conducted by Minardi et al. [75], where the researchers developed a type I collagen/elastin crosslinked blend (CollE). This material was used to fabricate both flat sheets and porous scaffolds as biomimetic meshes for ventral hernia repair. Both designs demonstrated biomechanical adequacy for immediate hernia defect repair, ensuring tissue restoration within six weeks and promoting neovascularization. Among the two architectures, the CollE scaffolds exhibited mechanical properties more closely aligned with native tissues. They also induced a higher expression of genes related to matrix deposition, angiogenesis, adipogenesis, and skeletal muscle formation compared to the CollE sheets.

Further innovation in mesh design was demonstrated in a study by Amato et al. [76], which introduced a tentacle-shaped mesh for repairing Spigelian hernias. This novel design, characterized by a central body with integrated radiating arms, allowed for a fixation-free approach and provided enhanced defect overlap. Tested on 54 patients, the mesh was positioned in the preperitoneal sublay, with the "tentacles" extending across the abdominal musculature. These arms were trimmed in the subcutaneous layer following fascia closure. This design facilitated rapid, safe, and fixation-free placement, resulting in negligible complications, no recurrences, and significantly reduced postoperative pain. The fabrication technique of the mesh also critically determines its properties. Currently, most meshes are manufactured through warp-knitting, a method in which fibers are curved into a meandering pattern to achieve elasticity and flexibility. This approach allows the mesh to adapt to bodily movements. However, warp-knitting also has limitations, such as higher ultimate load values and an inability to mimic the anisotropic mechanical behavior of the abdominal wall tissues [12,78]. Electrospinning has emerged as an alternative fabrication method, particularly for generating nano-range fibers. This versatile, cost-effective technique enables the creation of polymeric scaffolds with a high surface area-to-volume ratio and interconnected pores. However, electrospinning products often exhibit poor mechanical properties and limited control over pore structures [79,80].

In the pursuit of improved mesh designs, additive manufacturing techniques, particularly 3D printing, have garnered significant attention. This method facilitates the development of advanced, highly precise, and customizable patient-specific meshes that conventional fabrication methods cannot achieve. Additionally, 3D printing enables rapid and efficient surface modification of preexisting meshes [16,81,82]. Recent studies have reported the production of innovative 3D-printed meshes, including polylactic acid-acellular dermal matrix composites [83], personalized polypropylene-polyvinyl alcohol meshes loaded with ciprofloxacin [84], drug-doped polycaprolactone meshes containing alginate and gentamicin [85], tailored alginate-waterborne-polyurethane meshes [86], and custom polycaprolactone constructs impregnated with contrast agents such as iodinated, gadolinium, and barium [87]. A further advancement is the introduction of "4D printing," an additive manufacturing technique that incorporates time as the fourth dimension. This approach employs stimuli-responsive materials, such as smart thermopolymers, that can alter their shape in response to physicochemical or biochemical triggers. Such materials hold promise for creating meshes that dynamically adapt to the host-tissue environment, enhancing tissue integration and implant compliance. Although not yet applied to abdominal meshes, this technique has been successfully used in fabricating other adaptive polymeric scaffolds for biomedical applications [16,88-93], marking a foundation for future research in hernia repair. Another innovative method for mesh fabrication is embroidery technology, which offers a higher degree of design customization compared to warp-knitting. This technique allows thread orientation at nearly any angle with minimal effort and machine adjustments. Although not yet employed for hernia mesh fabrication, embroidery has shown potential in producing tissue-engineered scaffolds [78,79]. This technology could soon pave the way for implantable textiles with highly controlled designs, further advancing the field of hernia repair.

Clinical Trials

In addition to the previously mentioned advancements, numerous strategies have progressed to the clinical testing stages, highlighting the growing interest in this field and the pressing need for more effective abdominal meshes. A search on the ClinicalTrials.gov platform for the term "abdominal mesh" in relation to "hernia" (within the “condition or disease” field) yielded a total of 418 studies. Of these, 16 studies were categorized as “not yet recruiting,” 62 as “recruiting,” 8 as “active, not recruiting,” 218 as “completed,” 28 as “terminated,” 10 as “withdrawn,” and 76 as “unknown.” Regarding study phases, the trials included 35 in “phase 4,” 14 in “phase 3,” 17 in “phase 2,” 4 in “phase 1,” 1 in “early phase 1,” and 245 studies that were not phase-specific. A breakdown of trial types showed 308 interventional studies and 110 observational studies. Of the trials, 47 had publicly available results, while the remaining 371 did not. When filtering the search for "completed studies" with "results," a total of 38 clinical trials were identified.

Several of these trials have been cataloged with their respective identifiers, titles, interventions, phases, and references, providing a comprehensive overview of the ongoing efforts to improve abdominal mesh technologies. For instance, the study identified by NCT02451176, titled "A Prospective Randomized Trial of Biologic Mesh Versus Synthetic Mesh for the Repair of Complex Ventral Hernias," involves two mesh types—synthetic and biological—used for ventral hernia repair. This study, which is not phase-specific, employs devices such as the Davol Bard Soft Mesh and the LifeCell Strattice Reconstructive Tissue Biologic Mesh. Similarly, NCT02720042 focuses on the Phasix™ Mesh for midline hernia repair, while NCT01364233 investigates the use of condensed fenestrated PTFE mesh (MotifMESH) for non-sterile abdominal wall defects. Moreover, trials like NCT03247985 assess the comparative efficacy of tacking mesh versus self-fixating mesh in inguinal hernia repairs, and NCT00960011 evaluates the long-term results of self-gripping semi-resorbable mesh in open inguinal hernia repair. NCT01117337 contrasts non-fixation of mesh to mesh fixation in laparoscopic inguinal hernia repairs under spinal anesthesia, providing a comprehensive view of different procedural approaches and materials used in hernia repairs.

As for observational studies, NCT01863030 focuses on the use of Phasix™ Mesh in ventral and incisional hernia repairs, while NCT02206828 involves a registry study for the Symbiotic™ Composite Mesh in ventral hernia repair. Additional trials such as NCT00393887 and NCT01961687 explore various approaches to inguinal hernia repair, with the latter examining the Phasix™ Mesh for ventral or incisional hernia repair in a multicenter setting. The outcomes of several completed trials have been subject to extensive discussion in the literature. For instance, the study identified by NCT02451176, which compares the efficacy of biologic and synthetic meshes for single-stage repair of clean-contaminated and contaminated ventral hernias, has been explored in multiple articles. The trial, conducted on 253 adult patients from December 2012 to April 2019, with a follow-up period of two years, found that synthetic meshes had a higher two-year hernia recurrence risk when used for contaminated ventral hernias. Notably, the cost of the biologic mesh was over 200 times that of the synthetic mesh, despite both meshes showing similar safety profiles. Additionally, both types of mesh led to similar improvements in overall quality of life and hernia-related quality of life. In contrast, NCT00617357, which examines the repair of contaminated ventral hernias using Strattice™ (a porcine-derived, acellular dermal matrix), presents a different perspective. This trial investigated the impact of mesh placement in patients undergoing hernia repair. A total of 49 patients were involved, with mesh placed either retro-rectus (23 patients) or intraperitoneal (26 patients). According to associated publications, the retro-rectus placement resulted in successful reconstructions in over 70% of patients by the two-year follow-up benchmark, demonstrating the importance of mesh positioning in the success of the repair. Despite the larger hernia sizes in some cases, the study reinforced the potential benefits of utilizing Strattice™ mesh for complex hernia repairs.

Conclusion:

Hernia repair is a critical medical procedure that addresses the complex problem of abdominal wall defects. Over the years, significant progress has been made, especially with the development of surgical meshes, which have drastically improved the success rates of hernia surgeries. Surgical meshes offer mechanical support, reduce recurrence rates, and promote tissue healing. However, despite these advancements, challenges remain in choosing the ideal mesh material and technique for different types of hernias, particularly in complex or infected cases. Synthetic meshes, particularly those made from polypropylene, polyester, and expanded polytetrafluoroethylene (ePTFE), continue to dominate the field due to their durability, tensile strength, and cost-effectiveness. These materials have been shown to effectively withstand abdominal pressures and prevent hernia recurrence. However, their use is not without drawbacks. For example, synthetic meshes may trigger foreign body reactions, leading to complications such as adhesions, chronic sepsis, and erosion. As a result, they are contraindicated in cases of open abdomen repairs or contaminated surgical sites. Biological meshes, which are derived from human or animal sources, have emerged as a viable alternative, particularly in patients with high-risk profiles or in cases of infection. These meshes offer superior biocompatibility and reduced inflammatory responses, thus enhancing healing and reducing the risk of complications. However, their high cost and susceptibility to stretching over time limit their widespread application in routine hernia repairs. Composite meshes, which combine synthetic and biological materials, offer the best of both worlds, providing enhanced tissue integration while maintaining the mechanical strength necessary for hernia repair. This hybrid approach addresses the limitations of single-material meshes, offering a promising solution for complex cases. While the introduction of lightweight and antimicrobial meshes has improved clinical outcomes, further research is required to address ongoing challenges such as cost, long-term durability, and the need for standardized treatment protocols. Clinical trials are actively exploring new mesh materials, configurations, and surgical techniques to optimize hernia repair outcomes. In conclusion, the continued evolution of mesh technology holds great promise for improving the success rates of hernia surgeries and ensuring better patient outcomes. Further advancements in mesh design, material properties, and personalized treatment strategies will be key to overcoming the remaining hurdles in hernia repair.

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الاتجاهات الشائعة في إصلاح الفتاق: الشبكات - مراجعة محدثة للاتجاهات الجديدة

الملخص:

الخلفية: تعتبر الفتوق الجدارية البطنية حالة شائعة يمكن أن تؤدي إلى عواقب صحية كبيرة وضعف وظيفي. تؤثر الفتوق على ملايين الأشخاص حول العالم وغالبًا ما يتم علاجها جراحيًا. على مدار الستة عقود الماضية، تطورت تقنيات إصلاح الفتاق، وأصبحت الشبكات الجراحية هي العلاج القياسي. وعلى الرغم من التقدمات، لا يوجد "معيار ذهبي" معتمد عالميًا لإصلاح الفتاق، ولا يزال البحث المستمر يركز على تحسين المواد وتصاميم الشبكات.

الهدف: تهدف هذه المراجعة إلى تقديم تحديث شامل للاتجاهات الحالية في إصلاح الفتاق، مع التركيز على أنواع الشبكات المختلفة المتاحة، وخصائصها، والتطورات في علم المواد التي تحسن النتائج السريرية.

الطرق: تقوم المراجعة بتحليل مجموعة واسعة من الأدبيات، بما في ذلك الدراسات السريرية والابتكارات في إصلاح الفتاق، مع اهتمام خاص بالتطورات الأخيرة في تقنيات الشبكات. يتم تصنيف الشبكات إلى أنواع صناعية، بيولوجية، وتركيبية، مع تسليط الضوء على أحدث التطورات في المواد خفيفة الوزن، والطلاءات المضادة للبكتيريا، والتكوينات الهجينة.

النتائج: قدمت التطورات الأخيرة شبكات تتمتع بخصائص لاصقة محسنة، وميزات مضادة للبكتيريا، واندماج أفضل في جدار البطن. أدت الشبكات الخفيفة والمواد المركبة إلى تحسين الاستجابة البيولوجية، مما يقلل من خطر العدوى والمضاعفات. كما تبرز الدراسة التجارب السريرية المستمرة التي تستكشف التكوينات والمواد الجديدة للشبكات. بينما تظل الشبكات الصناعية الأكثر شيوعًا، أصبحت الشبكات البيولوجية والتركيبية بدائل مهمة في حالات معينة.

الاستنتاج: لا يزال إصلاح الفتاق يستفيد من التقدم في تقنيات الشبكات، مع تحسن واعد في تكامل الشبكات، والتوافق الحيوي، ونتائج المرضى. يتطور المجال نحو نهج أكثر تخصيصًا، بما في ذلك استخدام الشبكات الهجينة والتركيبية المصممة وفقًا لاحتياجات المرضى. يظل البحث المستمر أمرًا بالغ الأهمية لتحسين مواد وتقنيات الشبكات، مما يضمن نتائج سريرية أفضل وتقليل المضاعفات.

الكلمات المفتاحية: إصلاح الفتاق، الشبكات، الشبكات الصناعية، الشبكات البيولوجية، الشبكات التركيبية، الفتوق الجدارية البطنية، المواد الجراحية، التوافق الحيوي، التجارب السريرية، تقنيات الشبكات.