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Review Article

Nanotechnology approaches in abdominal wall reconstruction: A narrative review about scaffold and meshes

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ABSTRACT

Repairing abdominal wall defects poses challenges for surgeons. Although mesh reinforcement is commonly used for primary repair, nanotechnology has emerged as a promising approach for developing innovative repair techniques. Most research in this area focuses on fabricating scaffolds designed specifically for abdominal wall repair, particularly in cases of hernia. These scaffolds are engineered to replicate the structure and function of the native extracellular matrix. This review aimed to summarize the existing studies on the application of nanotechnology in abdominal wall reconstruction following injury or repair.

Introduction

Reconstructing large and complex abdominal wall defects, particularly those complicated by infection, presents a considerable clinical challenge.[1] These defects often arise due to hernias.[2] Currently, there is no universally accepted surgical approach or technique for effectively reconstructing such de-

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Table 1
Overview of the most used and available biological meshes. Culled from[3]

Biological mesh	Source	Manufacturer	Cross-linking	Sterilization	Size/thickness
Allomax	*Human dermis*	*Davol*	*NO*	*Gamma-irradiation*	*Size: 13 × 15 cm²*
Collamend	*Porcine dermis*	*Bard*	*Crossliked collagen and elastin*	*Ethylene oxide residuals*	*Size: 20.3 × 25.4 cm²*
FlexHD	*Human dermis*	*Musculoskeletal transplant Foundation/Ethicon*	*No*	*Aseptic processing*	*Size: 8 × 16 cm²*
FortaGen	*Porcine intestine*	*Organogenesis Inc.*	*Low level of cross-linking*		
Peri-guard	*Bovine pericardum*	*Synovis*	*Glutaraldehyde*	*Ethanol and propylene oxide*	
Permacol	*Porcine dermis*	*Covidien*	*Chemically cross-linked (diisocyanate)*	*Gamma-irradiation*	*Size: 1 × 4 cm²*
Strattice	*Porcine dermis*	*LifeCell*	*No*	*E-beam*	*Size: 20 × 20 cm²*
Surgisis	*Porcine intestine*	*Cook*	*No*	*Ethylene oxide residuals*	*Size: 20 × 20 cm²*
SurgiMend	*Fetal bovine dermis*	*TEI Biosciences*	*No*	*Ethylene oxide residuals*	*Size: 20 × 20 cm²*
Tutopatch	*Bovine pericardium*	*Tutogen*	*No*	*Gamma-irradiation*	
Veritas	*Bovine pericardium*	*Synovis*	*No*	*E-beam*	*Size: 12 × 25 cm²*
XenMatrix	*Porcine dermis*	*Bard Medical*	*No*	*E-beam*	*Size: 19 × 35.5 cm²*
Alloderm	*Human dermis*	*LifeCell Corp.*	*No*	*Aseptic proprietary process, freeze-dries dermis, and forgoes terminal gas sterilization*	*Size: 16 × 20 cm²*

fects.[3] Over time, the management of abdominal hernias has evolved from basic primary suture repair to more advanced methods involving biological mesh and scaffold repair.[4]

Nanotechnology has been used to develop repair methods for abdominal wall defects, primarily through the fabrication of scaffolds and biological meshes, which are often used in hernia repairs. Synthetic and biological meshes have seen advancements in this field.[5] Although synthetic meshes are effective in several clinical scenarios, the time required for cellular remodeling to achieve the necessary physical strength limits the use of absorbable non-biological meshes.[6] In contrast, biological meshes, derived from human or animal tissues, facilitate neovascularization and regeneration through the infiltration of native fibroblasts, making them preferable over synthetic meshes.[7]

Acellular matrices, which are biologically derived grafts, have been reported as being effective in abdominal wall reconstruction.[8] However, their remodeling rate into neotissue is low.[9] Table 1 provides an overview of the characteristics of various meshes used in abdominal wall reconstruction.[3]

This review aimed to summarize the application of nanotechnology in fabricated biological meshes and scaffolds used to repair abdominal walls.

Application of fabricated scaffolds in abdominal wall reconstruction in experimental studies

Hong and colleagues[4] showcased the utilization of a biodegradable elastomeric scaffold, crafted through electrospinning of a solution comprising poly-urea (PEUU) and porcine dermal extracellular matrix (dECM) digest. PEUU contributed to elasticity, flexibility, and mechanical support, while dECM was included to enhance the bioactivity and biocompatibility for reconstructing the abdominal hernia wall in a rat model.[5] Their findings indicated the absence of physical signs of herniation, infection, or tissue adhesion after one and two months with a scaffold containing their fabricated material.[6-10]

Moreover, they noted that the fabricated scaffolds containing dECM were notably thicker upon integration into the rat model, exhibiting evidence of smooth muscle actin-positive staining cells compared to the control group.[11-14] However, the dECM showed minimal influence on cellular infiltration and scaffold remodeling.[15]

Fanrong and colleagues also described the utilization of highly cellularized 3D-tissue constructs for repairing extensive abdominal wall defects. These constructs were created in vitro using poly (lactic acid)-collagen scaffolds within a flow perfusion bioreactor.[5] The scaffolds comprised a unique physical

structure, consisting of a collagen sponge embedded within the pores of a mechanically stable knitted mesh of poly (lactic acid), seeded with dermal fibroblasts.[16-20]

The cellularized 3D-tissue constructs cultured in vitro were further investigated through subcutaneous implantation in a rat model. The results indicated increased cellularity within the fabricated construct 28 days post-implantation.[21-23] Moreover, the in vivo model demonstrated notable cell stabilization and a moderate expression of extracellular matrix proteins, specifically collagen types I and III.[24-26]

In a separate experimental investigation conducted by Ayele and colleagues, they showcased engineered skeletal muscle tissue for the repair of abdominal wall defects. This involved the incorporation of myoblasts onto scaffolds that were cultured in vitro for 5 days.[6] The results revealed successful repair of abdominal wall defects using myoblast-seeded bovine tunica vaginalis compared to the control group.[27,28] Additionally, Ayele et al. observed that the seeded scaffolds facilitated the deposition of newly formed collagen fibers, with the presence of multinucleated myotubes and myofibers in contrast to the control group.

They concluded that the myoblast-seeded bovine tunica vaginalis holds promise as a scaffold for repairing large and complex abdominal wall defects.[29]

In a recent study, Zhicheng and colleagues demonstrated the application of vascular endothelial growth factor (VEGF)-loaded multi-walled carbon nanotubes (MWNT) combined with porcine acellular dermal matrices (ADM) composite scaffolds for repairing abdominal wall defects in vivo.[7] VEGF-loaded MWNTs were prepared using a modified plasma polymerization treatment, with a 5–10 nm thick poly(lactic-co-glycolic acid) film evenly integrated onto the MWNTs. The 3% MWNT composite group exhibited lower cytotoxicity and appropriate release performance, prompting further in vivo testing.[30-32]

Zhicheng and colleagues concluded that the controlled release of VEGF facilitated accelerated revascularization, contributing to the effective repair of abdominal wall defects using the fabricated composite scaffold. Moreover, they noted that the MWNTs scaffold demonstrated an efficient molecular transport system. However, they also observed a degree of cytotoxicity associated with MWNTs, highlighting the importance of exercising caution when considering the clinical application of this scaffold.

In a separate experimental investigation conducted by Deeken and colleagues, the efficacy of two novel bionanocomposite scaffolds was compared and assessed in a rodent model over a period of 3 months for abdominal wall repair.[33-35] These scaffolds comprised amine-functionalized gold nanoparticles (AuNP) and silicon carbide nanowires (SiCNW) crosslinked to an acellular porcine diaphragm tendon.[8]

In summary, the SiCNW bionanocomposite scaffolds extracted from the experimental rats 1 week post-implantation exhibited significant acute inflammation and mild chronic inflammation.[9] Additionally, after 21 days, immune cells, predominantly lymphocytes, were noted at the interface between the SiCNW scaffold and host tissue.[10] Ultimately, the researchers observed the absence of acute inflammation, alongside the evidence of vascularity, fibroblast proliferation, and deposition of new collagen.[11]

Moreover, upon extraction 1 week post-implantation, the AuNP bionanocomposite scaffolds exhibited signs of vascular and fibroblast proliferation, along with edematous granulation tissue.[12] At the scaffold-host interface, numerous immune cells, primarily lymphocytes, were observed.[13] However, after 21 days, no evidence of acute inflammation, vascular and fibroblast proliferation, or fat and muscle necrosis was noted upon explantation.[36-39] Deeken and colleagues ultimately concluded that compared to the SiCNW scaffolds, the AuNP bionanocomposite scaffolds demonstrated accelerated scaffold remodeling.[14-16]

Application of nanotechnology to meshes in abdominal wall reconstruction in clinical studies

Another utilization of nanotechnology in addressing abdominal wall defects involves the creation of AlloDerm, an acellular dermal matrix sourced from cadaveric human skin tissue.[17] This manufacturing process meticulously eliminates any cells that may provoke an immune response or graft rejection while preserving the extracellular matrix.[18] Notably, AlloDerm has been extensively studied, with approximately 984 cases reported across 23 clinical studies.[19,40]

Another application of nanotechnology in abdominal wall repair involves Surgisis, a biological mesh sourced from porcine small intestinal submucosa.[41–45] As described by Rosen, this mesh undergoes treatment with peracetic acid and is terminally sterilized with ethylene oxide without cross-linking.[46,47] Post-surgery, the mesh is gradually replaced by native tissue within approximately 6 months.[48] Although its durability has been extensively demonstrated in inguinal hernia repairs, its application in abdominal wall hernia repairs remains limited.[49] Additionally, there are reports of lesser-known meshes being used in the repair of abdominal wall defects.

Discussion

Abdominal wall allotransplantation is a vital reconstructive option when closing the abdominal wall is difficult and should be considered alongside visceral organ transplants. Neurotizing the abdominal wall allotransplant might provide functional benefits, and future research should focus on evaluating these functional outcomes.[50]

Repairing large, complex abdominal wall defects poses a significant challenge in clinical practice, particularly for those resulting from hernias. Currently, there is no universally accepted surgical technique for effectively reconstructing or repairing such defects. Nanotechnology has emerged as a promising approach to address this issue by developing innovative repair techniques. Various methods have been explored, including the fabrication of biological meshes such as AlloDerm, Permacol, and Surgisis, along with composite scaffolds that incorporate ADM and VEGF-loaded MWNTs generated through modified plasma polymerization. These approaches have shown efficacy in repairing abdominal wall defects. Additionally, bio-nanocomposite scaffolds such as AuNP bionanocomposite and SiCNW scaffolds have been shown to accelerate scaffold remodeling in experimental settings. Furthermore, experimental studies have demonstrated the successful repair of abdominal wall defects using scaffolds fabricated through single-stream electrospinning methods seeded with PEUU/dECM digest and biodegradable polyurethane.

Conclusion

Further extensive clinical studies are warranted to comprehensively evaluate the advantages and limitations of these fabricated scaffolds.

Availability of data and material

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Ethical approval and consent to participate

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Consent for publication

Not applicable.

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Contributors' statement page

Dr. Parham Khoshdani Farahani: conceptualized and designed the study, drafted the initial manuscript, and reviewed and revised the manuscript. Designed the data collection instruments, collected data, carried out the initial analyses, and reviewed and revised the manuscript. Coordinated and supervised data collection, and critically reviewed the manuscript for important intellectual content.

Conflict of interest

The authors deny any conflict of interest in any terms or by any means during the study.

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