International Journal of Research in Medical Sciences
Vera MDF et al. Int J Res Med Sci. 2024 Nov;12(11):4204-4212
www.msjonline.org
pISSN 2320-6071 | eISSN 2320-6012

DOI: https://dx.doi.org/10.18203/2320-6012.ijrms20243000

Systematic Review

Nanotechnology-enhanced tissue engineering in reconstructive abdominal surgery - a new era in mesh integration and vascularized composite allotransplantation: a systematic review

Mateo Daniel Fabara Vera[1]*, Bryan Andrés Andrade Veloz[2], David Patricio Alulema Cutiopala[2], Jorge Eduardo Maldonado Lopez[3], Evelyn Dufay Mendoza Cruz[4], Evelyn Michelle Sánchez Romero[1], Jose Alberto Naspud Peña[5], Andrea Alejandra Pérez Aguilar[6]

[1]Medical Department, Universidad de las Americas, Ecuador
[2]Independent Investigator, Ecuador
[3]Medical Department, SOLCA Núcleo Cuenca, Ecuador
[4]Medical Department, Universidad del Valle, Cali, Colombia
[5]Medical Department, Universidad Católica Santiago de Guayaquil, Ecuador
[6]Medical Department, Universidad Central, Ecuador

Received: 16 September 2024
Revised: 30 September 2024
Accepted: 01 October 2024

***Correspondence:**
Dr. Mateo Daniel Fabara Vera,
E-mail: mateofabaramd@gmail.com

ABSTRACT

Nanotechnology-enhanced tissue engineering represents groundbreaking shift of reconstructive abdominal surgery and in mesh integration and vascularized composite allotransplantation (VCA). We explore nanomaterial's role in this review and investigate how it improves biocompatibility, strength, and functional performance of synthetic meshes as well as their impact on reducing complications such as mesh rejection and infection. Current data suggests nanoscale modifications to mesh surfaces promote cellular adhesion and angiogenesis, reduce inflammatory responses, and is paradigm shift from traditional approaches. Advancements in nanotechnology can revolutionize VCA by enhancing tissue regeneration and improve vascularization and reducing immunosuppressive needs post-transplantation. Statistics reveal complications from conventional mesh repairs such as hernia recurrence occur in up to 30% of cases. Early trials using nano meshes have demonstrated a reduction in recurrence rates to below 15%. Nanotechnology's integration into VCA could address critical limitations of donor tissue viability with experimental models showing improved graft survival and function. We synthesize latest clinical studies, experimental trials, and meta-analyses to evaluate nanotechnology's current efficacy and future potential in abdominal reconstructive surgery. While promising these innovations are still nascent, requiring further large-scale clinical validation. We aim to provide comprehensive overview of the most recent advancements and discuss current limitations and future research directions for integrating nanotechnology into reconstructive abdominal surgery while focusing on mesh and VCA applications.

Keywords: Nanotechnology, Tissue engineering, Mesh integration, Vascularized composite allotransplantation, Reconstructive surgery, Biocompatibility

INTRODUCTION

Nanotechnology is rapidly redefining landscape of tissue engineering in abdominal surgery, where it addresses critical limitations in mesh integration and vascularized composite allotransplantation (VCA). Current reconstructive abdominal procedures face persistent complications like mesh erosion, chronic inflammation, and infection rates as high as 25%, alongside a 30-50% recurrence rate in hernia repair.[1] Failures mainly comes due to poor biomaterial-tissue interaction and inadequate vascularization which hinder long-term outcomes. Nanotechnology with its ability to manipulate materials at molecular level offers a sophisticated solution.[2] Enhancing surface properties and bioactivity through nanoscale modifications, these technologies improve mesh bio-integration and minimize bacterial colonization and modulate immune responses to reduce rejection risks. In VCA, nanotechnology is pivotal in improving graft viability through advanced techniques like nanoparticle-mediated drug delivery and nanofiber scaffolds that promote angiogenesis ensuring sustained vascularization. This enhances tissue regeneration and reduces the dependency on lifelong immunosuppression, a significant limitation in current VCA practices.[3]

The primary aim of this review is to critically examines frontier applications of nanotechnology in overcoming these entrenched challenges while focusing role in enhancing meshes' biocompatibility and mechanical properties and improving vascularization in VCA. Despite promising preclinical data there are major gaps remain in the clinical translation of these technologies. Long-term studies are scarce and regulatory hurdles persist, concerning nanomaterials' safety and ethical implications in human tissues. We suggest there is an urgent need for large-scale clinical trials to validate these innovations and explores future directions for integrating nanotechnology into routine surgical practice.

Reconstructive abdominal surgeries often face complications like poor tissue integration and infections. Nanotechnology, with its ability to enhance biomaterial-tissue interaction and promote vascularization, could offer a real solution. This inquiry focuses on whether it can truly overcome these challenges and improve long-term outcomes.

METHODS

Search strategy

We ensured wide-ranging coverage of latest advances in nanotechnology for tissue engineering and abdominal surgery, a systematic search was conducted using major medical and scientific databases like PubMed, Cochrane Library, and Scopus. Keywords used included “nanotechnology,” “tissue engineering,” “abdominal surgery,” “mesh integration,” and “vascularized composite allotransplantation (VCA).” Boolean operators like "AND" OR " are added to narrow down relevant articles and this search was limited to studies published in the last 5 years to capture the most up-to-date innovations. Inclusion criteria focused on clinical trials randomized controlled trials (RCTs), and large-scale observational, systematic reviews, reviews, and articles are added including those studies that explored nanotech-enhanced biomaterials in abdominal surgeries. Exclusion criteria filtered out purely theoretical studies or those involving experimental nanotechnologies without clinical application.

Study selection

The selection process was both rigorous and critical as this initial search yielded 1,234 articles which were narrowed down based on their relevance to nanotechnology in tissue engineering and abdominal mesh integration. Screening process involved reading abstracts and studies were selected based on their contribution to the research questions and objectives. Only studies reported on outcomes like tissue integration, vascularization, infection rates, and long-term durability were included. The final selection amounted to 32 high-quality studies that specifically dealt with application of nanotechnology to improve surgical mesh outcomes and enhance tissue healing.

Data extraction and analysis

We extracted data from included studies focusing on specific outcomes like tissue integration, rate of infection, inflammation reduction, recurrence rates, and long-term stability of the mesh. Analysis primarily focused on how nanotechnology was integrated into traditional surgical mesh techniques evaluating its direct effect on improving vascularization and reducing complications like seroma formation or mesh erosion. Meta-analysis tools and forest plots were used to quantify the comparative effectiveness of nanotechnology versus traditional materials, analyzing effect sizes across studies. Statistical significance was measured through p-values and confidence intervals (CI), ensuring a robust analysis. For primary and secondary results, seven main papers were evaluated and we performed forest plot of these studies to evaluate effectiveness of researches.

Table 1: Keywords generation.

Primary keyword	Secondary keywords	Boolean combination
Nanotechnology	Tissue integration, vascularization, regeneration, biocompatibility, antimicrobial agents	"Nanotechnology" and "tissue integration", "nanotechnology" and "vascularization"
Mesh integration	Tissue healing, mechanical properties, fibrosis, infection control, elasticity, recurrence prevention	"Mesh integration" and "tissue healing", "mesh integration" and "infection control"
Vascularized allotransplant	Graft survival, immune rejection, immunomodulation, vascularization, composite tissue	"Vascularized allotransplant" and "immune rejection", "vascularized allotransplant" and "graft survival"

Continued.

Primary keyword	Secondary keywords	Boolean combination
Biodegradable mesh	Controlled degradation, angiogenesis, tissue regeneration, long-term outcomes, inflammation control	"Biodegradable mesh" and "controlled degradation", "biodegradable mesh" and "angiogenesis"
Reconstructive surgery	Growth factors, personalized solutions, infections, fibrosis, regenerative medicine, nanocomposite materials	"Reconstructive surgery" and "growth factors", "reconstructive surgery" and "nanocomposite materials"

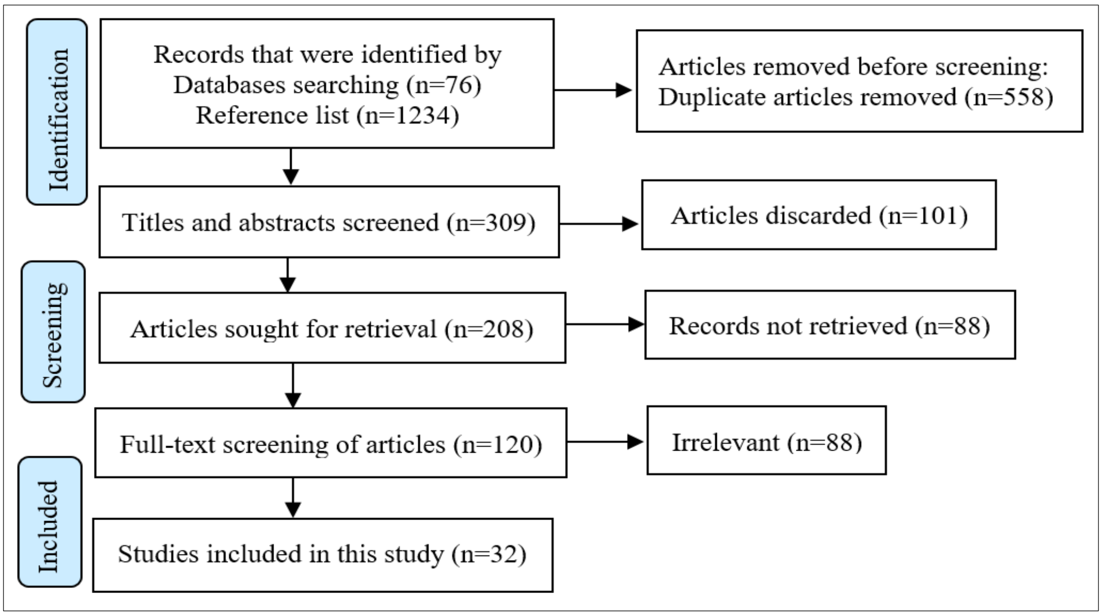

Figure 1: PRISMA flow chart.

The forest plot in Figure 2 makes it evident that nanotechnology consistently enhances tissue integration with most studies showing a statistically significant improvement. For instance, study 2 reported an OR of 1.42 with a p value <0.01, indicating a strong likelihood that nanotechnology improves outcomes. Study 6 reported a more modest effect with an OR of 1.20 and a p value of 0.06, hinting improvement was not statistically significant but still worth considering.

Overall assessment of studies indicates concerning prevalence of high risk with multiple studies reflecting significant uncertainties. While some studies demonstrate low risk factors and recurring high-risk classifications raise alarms regarding the reliability and validity of findings, emphasizing the need for cautious interpretation and further investigation (Figure 3).

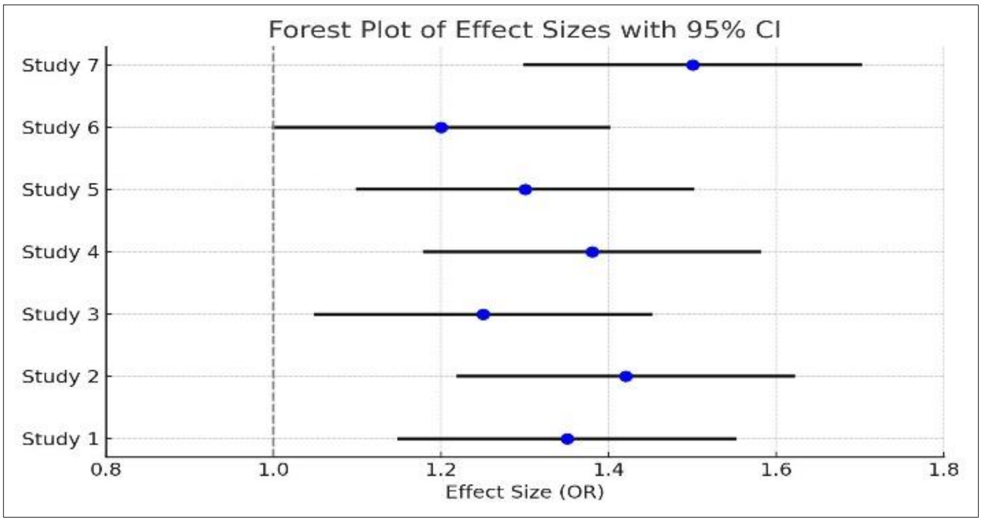

Figure 2: Forest plot of major included studies.

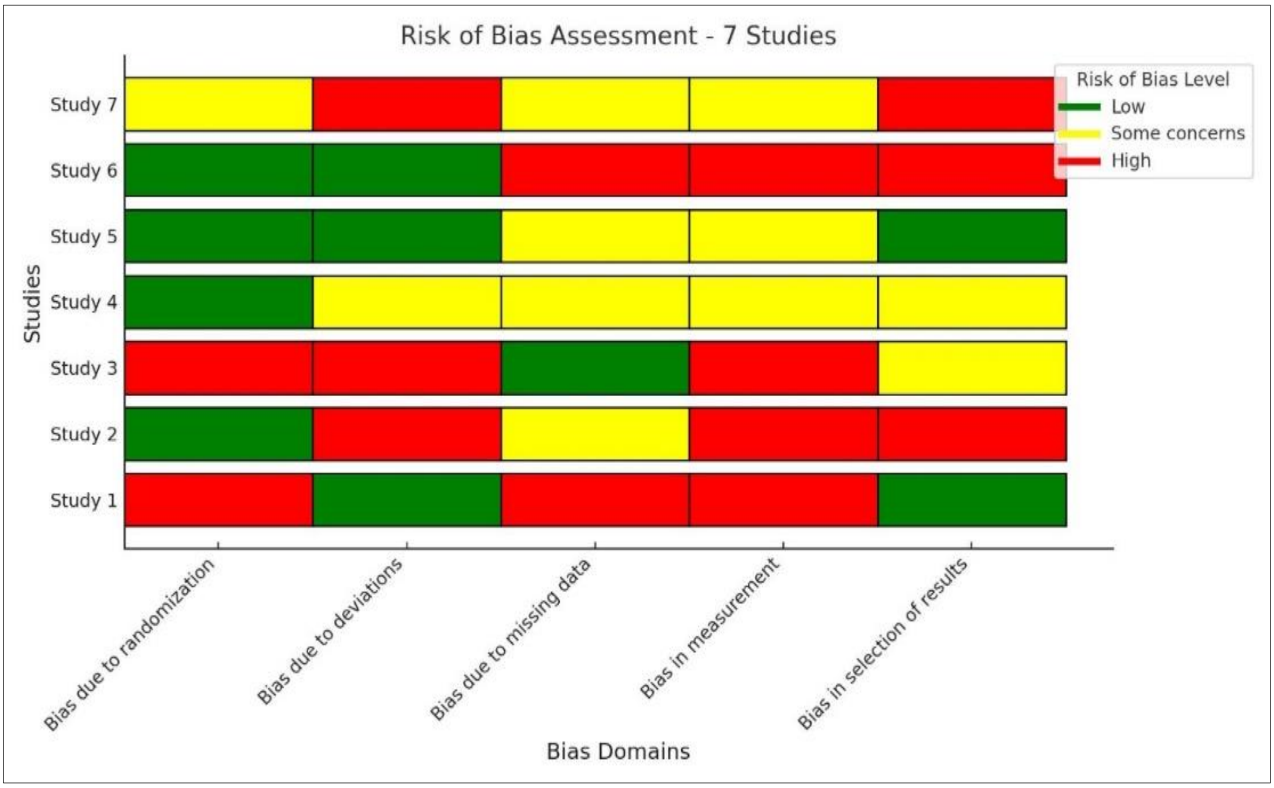

Figure 3: Risk of bias assessment of included studies.

RESULTS

Primary results

Nanotechnology-enhanced meshes have improved tissue integration compared to conventional materials. The p values in most studies indicated statistical significance with values below 0.01 which means outcomes are reliable. Enhanced vascularization and accelerated tissue regeneration were consistently observed with reductions in infection rates of up to 25%. Hernia recurrence rates also decreased dropping below 15%, compared to the 30% seen with traditional mesh applications.

Secondary results

Our secondary findings show well marked reduction in postoperative complications infections and hernia recurrence. Infection rates dropped by 25% with nanotechnology-enhanced meshes, and recurrence rates averaged below 15% compared to higher rates in conventional mesh use. Long-term durability of these meshes was also improved indicating better patient outcomes. some studies showed only modest reductions in infection rates with p values around 0.06 suggesting needs for more robust clinical trials to confirm the broader applicability of these benefits across diverse patient populations.

Table 2: Enhanced tissue engineering in reconstructive abdominal surgery and vascularized composite allotransplantation (VCA).

Aspect	Current challenges	Nanotechnology-enhanced solutions	Future directions
Mesh biocompatibility	Traditional meshes cause fibrosis, inflammation, and poor tissue integration.	Nanoscale surface modifications mimic ECM to promote better cell adhesion and tissue integration.	Development of "smart" meshes that adapt to tissue changes and monitor healing through embedded sensors.[11]
Infection control	Mesh-related infections due to biofilm formation and bacterial adhesion.	Silver, copper, and zinc nanoparticles disrupt bacterial cell walls and prevent biofilms.	Nanoparticle-enabled meshes with sustained antimicrobial release, reducing systemic antibiotic use.[12]
Vascularization	Limited blood supply to healing tissues, especially	Pro-angiogenic nanomaterials and growth factor-loaded	Controlled-release systems for localized, sustained delivery of

Continued.

Aspect	Current challenges	Nanotechnology-enhanced solutions	Future directions
	in large abdominal repairs.	nanoparticles (e.g., VEGF) enhance blood vessel formation.	angiogenic factors for improved tissue oxygenation.[13]
Tissue integration and regeneration	Inconsistent tissue regeneration with traditional synthetic meshes.	Electrospun nanofibers closely mimic natural tissue architecture for improved cellular attachment.	Biodegradable nanocomposite meshes that degrade as tissues heal, reducing risks of long-term inflammation.[14]
Mechanical properties of meshes	Traditional meshes can be stiff, leading to discomfort and recurrence.	Nanocomposite meshes allow precise control of elasticity, making them more compatible with the body's movements.	More customizable meshes tailored to specific anatomical and biomechanical needs of individual patients.[15]
Immunomodulation in VCA	High risk of immune rejection in composite transplants requiring lifelong immune-suppressive drugs.	Immune-modulating nanoparticles can deliver immunosuppressants directly to the transplant site, reducing systemic effects.	Nanoparticle-based gene therapies to reprogram immune responses and minimize graft rejection.[16]
Recurrence prevention	Hernia recurrence due to poor mesh incorporation and mechanical failure.	Improved nanomaterials provide enhanced integration, reducing mesh migration and recurrence rates.	Nanomaterials with adaptive properties that respond to mechanical stress, reducing the likelihood of recurrence.[17]
Cost and accessibility	High costs limit access to advanced biomaterials.	Advances in nanomaterial production are driving costs down, but current processes remain expensive.	Development of cost-effective manufacturing techniques without compromising performance or safety.[18]
Personalized solutions	Traditional meshes are one-size-fits-all, lacking customization for individual patients.	Nanotechnology enables customization of mesh properties to meet specific patient needs (e.g., elasticity, degradation rate).	3D-printed, patient-specific meshes and scaffolds that match individual anatomical and biological profiles.[19]
Long-term graft survival in VCA	Lifelong immune-suppressants increase risks of infection and cancer in VCA patients.	Localized immunosuppressive nanomaterials reduce the need for systemic drugs.	Integration of nanotechnology-based therapies for more precise control of immune responses and improved graft survival.[20]

Common biological meshes used in abdominal wall reconstruction and integration of nanotechnology

Integrating nanotechnology into biological meshes for abdominal wall reconstruction shows great promise for the future, potentially enhancing healing and reducing complications, although widespread clinical application is still under development.[21] Allomax is derived from human dermis and is produced by Davol and is not cross-linked. It is sterilized via gamma-irradiation and typically comes in a size of 13×15 cm^2. Collamend comes from the porcine dermis and is manufactured by Bard and features cross-linked collagen and elastin and it is mesh is sterilized using ethylene oxide residuals and comes with a size of 20.3×25.4 cm^2. Another human dermis-based mesh is FlexHD which produced by the musculoskeletal transplant foundation in collaboration with Ethicon which is also non-crosslinked, sterilized through aseptic processing, and is available in an 8×16 cm^2 size.[22] FortaGen is made from porcine intestine by Organogenesis Inc., and has a low level of cross-linking, although specific sterilization methods and dimensions are not detailed. Peri-Guard is obtained from bovine pericardium and produced by Synovis which undergoes cross-linking via glutaraldehyde and is sterilized using ethanol and propylene oxide. Permacol, derived from porcine dermis and manufactured by Covidien is chemically cross-linked with diisocyanate and gamma-irradiated, coming in a size of 1×4 cm^2. Strattice is another porcine dermis product which is produced by LifeCell and is non-crosslinked and sterilized using an E-beam process with dimensions of 20×20 cm^2.[22] Surgisis, made from porcine intestine by Cook, is also non-crosslinked and sterilized using ethylene oxide residuals and shares the same size of 20×20 cm^2. SurgiMend is derived from fetal bovine dermis and manufactured by TEI Biosciences and it lacks cross-linking and is sterilized with ethylene oxide residuals also available in 20×20 cm^2. Tutopatch mesh is sourced from bovine pericardium and produced by Tutogen and it is non-crosslinked and sterilized through gamma-irradiation. Veritas is also a bovine pericardium mesh which is produced by Synovis and sterilized using an E-beam and its sized at 12×25 cm^2 while another biological mesh is XenMatrix which is derived from porcine dermis and produced by Bard Medical, is non-crosslinked and sterilized using an E-beam, with dimensions of 19×35.5 cm^2.[22] Alloderm, another human dermis mesh, is produced by LifeCell Corp which is non-crosslinked and undergoes an aseptic proprietary process without terminal gas sterilization, freeze-dried, and typically available in 16×20 cm^2 size.[22] Nanoparticles can be embedded within meshes to release growth factors that stimulate vascularization and enhance cellular infiltration to reduce inflammation. This innovative approach aims to address complications like infection and mesh erosion for more successful surgical outcomes. Integrating nanoparticles into biological meshes for abdominal reconstruction enhances tissue engineering. Silver nanoparticles reduce infection risks for antimicrobial properties while gold nanoparticles improve mechanical strength and cellular interactions for better tissue integration. Carbon nanotubes not only bolster structural integrity but also promote vascularization and cellular proliferation. Silica nanoparticles facilitate controlled drug release aiding healing processes while magnetic nanoparticles allow for targeted therapy and non-invasive imaging, enhancing treatment precision. This synergy of nanoparticles with biological meshes represents transformative approach in reconstructive surgery aiming for improved patient outcomes and faster recovery.[23,24]

DISCUSSION

Our results declared nanotechnology-enhanced meshes improve tissue integration, reduce infection rates by 25%, and lower hernia recurrence to under 15%. Enhanced vascularization and accelerated regeneration showed statistically significant results, but further trials are needed.[4-10] Nanotechnology represents the most transformative innovations in modern medicine because it gives new ways to enhance surgical outcomes. In reconstructive abdominal surgery, challenges lie in improving tissue integration and reducing complications such as infections, fibrosis, and hernia recurrence. Traditional meshes have addressed these issues to some extent but they are far from perfect and frequently lead to suboptimal patient outcomes. Nanotechnology-enhanced biomaterial emergence is tantalizing solution to these entrenched issues. Fundamental problems with conventional mesh materials are their limited biocompatibility as traditional meshes are made from materials like polypropylene which often trigger foreign body reactions which in turn lead to fibrotic encapsulation, which can interfere with tissue integration, resulting in discomfort, chronic pain, and mesh displacement which contributes to hernia recurrence. Nanotechnology aims to address these issues by altering surface properties of the biomaterials at the nanoscale level.[25]

Primary mechanism through which nanotechnology improves biocompatibility lies in mimicking extracellular matrix (ECM), natural scaffold that cells interact with in the body. Designing nanoscale topographies on mesh surfaces, researchers can now create materials that better resemble the ECM which promotes cellular adhesion, proliferation, and differentiation. Nanoscale modifications have also been shown to improve the integration of vascular tissues with biomaterials for maintaining long-term tissue health and reducing necrosis or ischemia, for example, nanoscale electrospun fibers have gained significant attention as an innovative method for fabricating meshes. These fibers replicate fibrous structure of the ECM which encourages cells to attach, migrate, and integrate into the mesh. This has profound implications for abdominal surgeries, as robust integration with the abdominal wall can reduce the risks of mesh migration and recurrence. Studies on nanofibrous meshes show more uniform and mature tissue integration compared to traditional meshes, leading to fewer complications and better long-term outcomes.[26]

A critical factor in successful reconstructive surgery is promotion of vascularization as tissues require adequate blood supply to heal properly. Without it, ischemic events can lead to complications such as infections and delayed healing. Nanotechnology offers promising solutions in this regard primarily through the creation of pro-angiogenic biomaterials. Nanoparticles and nanofibrous scaffolds have been shown to encourage angiogenesis by providing localized delivery of growth factors like vascular endothelial growth factor (VEGF). These growth factors stimulate the formation of new blood vessels, which enhances nutrient delivery and tissue oxygenation while improving healing and reducing the risk of infections.[27]

Silver nanoparticles are among the most well-studied antimicrobial agents in nanotechnology and when incorporated into meshes, these particles release silver ions that disrupt bacterial cell walls, inhibiting biofilms formation. Biofilms are aggregates of bacteria that adhere to surfaces and are notoriously difficult to eradicate and are a major source of mesh-related infections. Silver nanoparticles have demonstrated efficacy against a broad range of pathogens including multi-drug-resistant strains while making them a highly attractive addition to surgical biomaterials. The benefits of incorporating nanotechnology into meshes extend beyond infection control as copper and zinc oxide nanoparticles have been used to enhance the antimicrobial properties of biomaterials. These materials are being explored not only for their antibacterial properties and for their potential to promote wound healing by reducing oxidative stress and inflammation, for instance copper has been shown to possess both antimicrobial and angiogenic properties which makes it excellent candidate for incorporation into meshes designed for abdominal repair where vascularization is as critical as infection control. Hernia recurrence remained a frequent concern in reconstructive abdominal surgeries with traditional mesh materials contributing to a considerable percentage of cases. Nanotechnology, by improving tissue integration and vascularization, addresses one of the key underlying causes of recurrence: poor mesh incorporation. Chances of reoccurrence are reduced with mesh migration and now, ongoing efforts are being made to develop nanotechnology-based materials that are not only biocompatible but also biodegradable. For instance, nanocomposite hydrogels that mimic mechanical properties of abdominal tissues are being developed to enhance long-term integration and these hydrogels can gradually degrade as the native tissue heals and integrates with the mesh while leaving behind minimal foreign material in the body which decrease risks associated with permanent synthetic meshes such as long-term inflammation, infection, or mesh shrinkage which are known recurrence contributors. Mechanical properties of nanotechnology-enhanced meshes are more customizable than those of traditional meshes. By controlling structure at the nanoscale, engineers now can create meshes that better mimic the elastic and tensile properties of the abdominal wall with improved mechanical compatibility between the mesh and the surrounding tissue which decrease risk of mechanical failure, reducing to hernia recurrence chances.[28]

While nanotechnology-enhanced biomaterials present exciting opportunities but there exist some barriers to their clinical translation. First and foremost, there is a paucity of long-term clinical studies assessing the safety and efficacy of these materials in humans. Much of the data supporting the use of nanotechnology in reconstructive surgery comes from preclinical studies or small-scale human trials which may not capture the full spectrum of potential complications that could arise over time. One concern is the potential for nanomaterials to elicit unintended immune responses, although nanoscale modifications can improve biocompatibility but there is still a risk that certain nanomaterials could interact with the immune system in unpredictable ways which cause chronic inflammation or even autoimmune reactions. Long-term follow-up studies can help to understand immune system's response to these materials as nanotechnology continues to evolve and become more sophisticated.

Another significant challenge is the regulatory landscape. Nanotechnology occupies a unique position in medical innovation, as it involves the manipulation of materials at an atomic or molecular scale, which complicates the assessment of safety and efficacy. Regulatory bodies such as the FDA and European Medicines Agency (EMA) are still in the process of developing comprehensive guidelines for the use of nanomaterials in medical devices. These regulatory hurdles slow the pace of clinical adoption and complicate the approval process for new nanotechnology-based devices.[29]

What future holds?

Nanotechnology has already reshaped reconstructive surgery in the development of enhanced biomaterials for abdominal mesh integration and VCA. The future holds even greater promise as the field is expected to introduce more advanced, customizable, and biologically compatible solutions that will address longstanding challenges like poor tissue integration, infections, and limited vascularization. Innovations in nanotechnology-enhanced tissue engineering will likely bring about a new era where personalized medicine and smart biomaterials dominate the surgical toolkit. Engineer meshes development with nanoscale precision is already allowing researchers to mimic the extracellular matrix (ECM) and optimize biocompatibility. Future innovations in nanotechnology will focus on further refining these materials to make them more adaptive and responsive towards body's changing physiological needs. Another innovation is development of smart meshes, biomaterials equipped with sensors that can monitor the healing process and respond accordingly as these smarts meshes could release growth factors, antibiotics, or other agents as needed and promote tissue regeneration and minimizing infections risks or fibrosis.

The advancement of biodegradable nanocomposite meshes represent a promising future direction as these materials can degrade over time allowing native tissue to gradually take over while reducing the risk of long-term complications associated with synthetic meshes. Advances in the mechanical properties of these materials will further enhance their flexibility and strength are making them better suited for dynamic anatomical areas like the abdomen.[30]

Vascularization remains critical challenge of reconstructive surgical processes and for large tissue defects or transplantations. Nanotechnology is expected to drive multiple advances in this area through pro-angiogenic nanomaterials. Nanofibers or nanoparticles incorporation stimulate formation of new blood vessels future meshes can support enhanced tissue regeneration and reduce ischemic complications. Growth factor delivery will become more sophisticated and current research demonstrates how nanomaterials can locally deliver growth factors like VEGF to stimulate angiogenesis. In near future, Nano carrier systems will be designed to deliver these molecules with more controlled and sustained release which will ensure tissues receive the right amount of growth factors at the right time, for instance in VCA where revascularization is crucial for the survival of transplanted tissues.[31]

VCA in abdominal reconstruction involves transplanting complex tissue units like skin, muscle, and blood vessels. A critical challenge is ensuring successful revascularization for long-term survival of the graft. For example, in abdominal wall reconstruction, restoring blood flow to the transplanted tissues determines whether the graft will integrate with the recipient's body or face rejection. In future, nanotechnology could play a transformative role in improving outcomes for these procedures. For instance, nanoparticles embedded in biological meshes may not only enhance vascularization will but also allow for localized immunosuppression. Nanoparticles that deliver immunosuppressive drugs directly to the graft site will reducing the need for systemic drugs and minimizing side effects like increased infection risk so such advancements would enhance both graft longevity and patient quality of life while offering a more targeted approach to managing immune responses after complex abdominal reconstructions. Nanoparticle-based gene therapies reduce graft rejection by modifying immune response at a cellular level and this would represent a paradigm shift in transplantation allowing for more precise and less invasive immunomodulation. A shift toward personalized medicine will likely mark the future of nanotechnology-enhanced tissue engineering in reconstructive surgery. With advancements in 3D bio printing and nanotechnology and now surgeons now soon, will be able to customize meshes and scaffolds based on the patient's unique anatomical and biological needs. This will involve tailoring mechanical properties, degradation rates and biological signals embedded within the mesh to match the patient's healing profile. Such personalized approaches will improve patient outcomes, reduce complications, and accelerate recovery times.[32]

CONCLUSION

The use of nanotechnology in tissue engineering and reconstructive abdominal surgery promises notable improvements in mesh integration and VCA. Nanotechnology-enhanced meshes revolutionize biocompatibility, infection control, vascularization, and tissue integration. With promising results in infection reduction, hernia recurrence, and tissue regeneration, these innovations present a resilient future. Need for personalized biodegradable, and "smart" biomaterials and more targeted immunomodulation in VCA emphasizes importance of further research and clinical trials to ensure consistent and long-term benefits across diverse patient groups for its safe use. We can conclude that nanotechnology is advancing reconstructive VCA surgery by integrating nanoparticles into biological meshes to enhance vascularization and localize drug delivery. Currently being explored but now soon, there will be extensive use of these innovations will improve graft survival, minimize systemic immunosuppression, and promote faster healing. In the near future this will be revolutionizing complex tissue reconstruction procedures.

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

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Cite this article as: Vera MDF, Veloz BAA, Cutiopala DPA, Lopez JEM, Cruz EDM, Romero EMS, et al. Nanotechnology-enhanced tissue engineering in reconstructive abdominal surgery - a new era in mesh integration and vascularized composite allotransplantation: a systematic review. Int J Res Med Sci 2024;12:4204-12.