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Editorial

Nanotechnology Applications in Surgical Wound Healing

N Gurunathan*

Assistant Professor, Department of Veterinary Surgery and Radiology, Rajiv Gandhi Institute of Veterinary Education and Research, Puducherry, India

***Corresponding Author:** N Gurunathan, Assistant Professor, Department of Veterinary Surgery and Radiology, Rajiv Gandhi Institute of Veterinary Education and Research, Puducherry, India.

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Abstract

Nanotechnology has emerged as a transformative tool in the field of regenerative medicine and surgical wound management. Nanomaterials, owing to their unique physicochemical and biological properties, enhance wound healing by promoting cellular proliferation, angiogenesis, antimicrobial activity, and controlled drug delivery. The incorporation of nanoparticles into dressings, gels, and scaffolds has shown superior healing outcomes compared to conventional therapies. This review highlights recent advances, mechanisms, and applications of nanotechnology in surgical wound healing in veterinary and biomedical practice.

Keywords: Nanotechnology; Nanoparticles; Wound Healing; Nanofibers; Antimicrobial; Tissue Regeneration

Introduction

Wound healing is a dynamic process involving hemostasis, inflammation, proliferation, and remodelling. Surgical wounds, although created under aseptic conditions, are prone to infection, delayed healing, and excessive inflammation. Traditional therapies often fail to provide optimal moisture, antimicrobial protection, and bioactive stimulation for regeneration. Nanotechnology, defined as the manipulation of materials at the scale of 1–100 nanometers, offers promising strategies to overcome these limitations. Nanomaterials interact with cellular and molecular components at the biological interface, accelerating tissue repair while minimising infection risk [1].

Mechanisms of nanoparticle action in wound healing

Nanoparticles facilitate wound healing through multiple mechanisms:

- **Antimicrobial Activity**: Silver, zinc oxide, and copper nanoparticles disrupt bacterial membranes and prevent biofilm formation.
- **Enhanced Cell Proliferation**: Nanostructured surfaces promote fibroblast and keratinocyte adhesion, aiding re-epithelialization.
- **Angiogenesis Stimulation**: Nanocarriers releasing VEGF or nitric oxide induce neovascularisation for nutrient supply.
- **Controlled Drug Release:** Nanocarriers ensure sustained delivery of antibiotics, growth factors, and anti-inflammatory agents.
- **Oxidative Stress Reduction:** Antioxidant nanoparticles neutralise reactive oxygen species (ROS), preventing tissue damage.

Types of nanomaterials used in wound healing

Nanomaterial	Key Function	Mechanism/Effect
Silver nanoparticles (AgNPs)	Antimicrobial	Destroy bacterial cell membranes, inhibit DNA
Zinc oxide nanoparticles (ZnO NPs)	Anti-inflammatory, UV protection	Regulate cytokines, promote epithelialization
Gold nanoparticles (AuNPs)	Antioxidant, angiogenic	Stimulate fibroblast migration, enhance collagen synthesis
Chitosan nanoparticles	Biodegradable carrier	Promote hemostasis and sustained drug release
Silica nanoparticles	Growth factor delivery	Provide scaffold for tissue integration
Polymeric nanoparticles (PLGA,PEG)	Drug/gene delivery	Controlled and targeted release for localized action

Nanotechnology-based wound healing systems

- **Nanoparticle-Infused Dressings:** Incorporating nanoparticles into wound dressings improves antimicrobial protection and moisture retention. Silver nanocomposite hydrogels show rapid infection control in contaminated surgical wounds. ZnO–chitosan films accelerate epithelialization and reduce scarring in canine skin wounds [2].
- **Nanofiber Scaffolds:** Electrospun nanofibers mimic the extracellular matrix (ECM), providing a 3D structure for cell attachment. Collagen–PCL nanofibers facilitate fibroblast proliferation and vascularisation. Silk fibroin nanoscaffolds enhance the tensile strength and elasticity of regenerated tissue.
- **Nanoemulsions and Gels:** Topical nanoemulsion-based gels containing silver or herbal nanoparticles improve drug penetration and provide a localised antimicrobial effect.
- **Nanocarrier-Enhanced Growth Factors:** Nanoparticles loaded with EGF, VEGF, or PDGF promote sustained angiogenic stimulation, avoiding degradation by wound proteases.
- **Smart Nanoparticles**: Responsive nanoparticles release drugs based on pH, temperature, or enzyme activity within the wound microenvironment.

Phases of wound healing and nanoparticle roles

Healing phase	Biological activity	Nanotechnological role
Inflammatory Phase	Clot formation, immune cell infiltration	Antimicrobial nanoparticles reduce bacterial load
Proliferative Phase	Fibroblast migration, angiogenesis	Gold and zinc nanoparticles enhance collagen synthesis
Remodeling Phase	Collagen maturation and tissue strengthening	Polymer-based nanoscaffolds support ECM reorganization

Comparative efficacy of nano-based vs conventional therapies

Parameter	Conventional dressing	Nanotechnology-based dressing
Healing rate	Moderate	30–50% faster
Infection control	Variable	Broad-spectrum antimicrobial
Moisture retention	Limited	High due to hydrogel structure
Drug delivery	Topical, short-term	Controlled, sustained release
Collagen deposition	Slower	Enhanced via nanoscaffold integration

Experimental studies in dogs and rabbits have shown that AgNP-impregnated collagen dressings significantly increase epithelialization rate and tensile strength compared to plain collagen membranes [3-5].

Veterinary applications

- **Post-surgical incision management**: Silver nanoparticle hydrogels reduce infection and inflammation.
- **Burn and degloving wounds:** Nanofiber mats provide rapid granulation tissue formation.
- **Orthopaedic implant coatings:** Titanium nanoparticles improve osseointegration and reduce postoperative infection.
- **Ophthalmic surgeries:** Nanoformulated antibiotics and lubricants aid in corneal wound healing.

Safety and biocompatibility

- Although nanoparticles enhance healing, safety concerns exist regarding cytotoxicity and bioaccumulation.
- Biocompatible carriers such as chitosan, alginate, and PLGA minimise toxicity.
- Dosing, particle size (<100 nm), and controlled degradation are critical for safe therapeutic use.
- Regulatory authorities recommend preclinical cytotoxicity and biodegradation assessments before clinical application.

Recent advances and future prospects

- **Green Synthesis of Nanoparticles**: Eco-friendly methods using plant extracts reduce chemical toxicity.
- **Hybrid Nanocomposites:** Combining metallic and polymeric nanoparticles for synergistic healing.
- **Stem Cell–Nanoscaffold Integration**: Nanomaterials support stem cell proliferation and differentiation in chronic wounds.
- **3D Bioprinted Nano-Dressings:** Personalized dressings with embedded nanomaterials and bioactive molecules.
- **Nano-Robots:** Future potential for micro-level debridement and precision drug delivery in surgical wounds.

Conclusion

Nanotechnology offers significant advancements in the field of surgical wound healing by enabling targeted drug delivery, infection control, and accelerated tissue regeneration. Nano-engineered dressings and scaffolds provide a microenvironment conducive to faster epithelialization and reduced scarring. While promising, standardization of nanoparticle synthesis, dosage safety, and long-term biocompatibility remain vital for clinical translation. The integration of nanotechnology into veterinary and human surgical practice marks a revolutionary step toward next-generation regenerative medicine.

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