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ELECTROSPINNING AND FORMATION OF NANOFIBROUS WOUND HEALING MATERIAL BASED ON BIOPOLYMER

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Abstract- In order to create the ideal microenvironment for effective tissue repair, wound dressings are crucial. An ideal dressing prevents microbial contamination of the wound, preserves moisture balance, permits gaseous exchange, absorbs excess exudate, and promotes extracellular matrix formation and cell proliferation. Appropriate dressing materials minimize pain, speed up healing, and prevent scarring in both acute and chronic wounds. However, there are a number of drawbacks to traditional wound dressings like cotton bandages and gauze. They frequently stick to the surface of the wound, inflict further damage when removed, retain moisture poorly, and provide little antimicrobial protection. difficulties in creating cutting-edge materials for wound dressings Key: One of the main challenges in creating materials for wound healing is striking the ideal balance between moisture retention and exudate absorption. The main obstacles may also include preventing microbial colonization without causing cytotoxicity, guaranteeing biocompatibility and non-immunogenicity, and offering adequate mechanical strength and flexibility. It's also crucial to enable controlled drug or bioactive agent released.

Keywords: Wound dressings**,** Tissue repair and regeneration**,** Moisture balance**,** Exudate absorption**,** antimicrobial protection**,** Biocompatibility**,** Controlled drug release.

INTRODUCTION

The restoration of the integrity of body tissues damaged due to injury is an inherent biological function (healing). Healing is a multi-step, complex process made up of multiple biological processes (cellular processes) and chemical processes (molecular processes) that work together to repair tissue from injury. Acute wounds follow the general sequence of haemostasis, inflammation, proliferation, and remodelling as they progress through healing; chronic wounds (ie, diabetic foot, venous stasis ulcers, pressure ulcers, and wounds caused by burns), however, do not always heal in a linear fashion. The increasing rates of diabetes, vascular disease, traumatic injury, and an aging population have created a higher demand for advanced technologies used to treat wounds. Traditional dressings (eg, cotton gauze, bandage, simple film dressing) generally are used as a barrier against contamination, not to promote tissue healing and to maintain the optimal conditions for wound healing. On the contrary, the contemporary wound management approaches integrate biocompatible scaffolds that provide an optimal environment for promoting cell adhesion, blood vessel formation (commonly known as angiogenesis), resisting infections by microorganisms, and controlled release of drugs. Among various emerging technologies, the electrospinning of nanobubbles' scaffolds has emerged as being of much interest due to their ability to replicate the nanostructure of extracellular matrices (ECM). Since Reneker first established a means of creating nanofibers by electrospinning in the early 1990s, a large body of work has expanded this field to include biomedical and regenerative uses for these nanofibers. Electro spun biopolymer-based nanofibers have many advantages, including being biodegradable, biocompatible, and having biological activity. Together, these properties make them very attractive as new materials for wound healing.

1.1 CHALLENGES IN DEVELOPING ADVANCED WOUND DRESSING MATERIALS

The main difficulty in developing new types of wound healing materials is how to dry the wound out while at the same time retaining enough moisture across the whole surface area of the dressing (and therefore protect the tissue underneath). Another significant challenge will be preventing any bacterial growth on the dressing (which would happen if there was no moisture) and not causing any additional damage to the cells underneath either through cytotoxicity or allergy. Also, another main problem will be ensuring that the dressing is strong enough, flexible enough and biocompatible with the body so as to allow for normal wound healing. Finally, controlling how quickly drugs or bioactive substances are released by the dressing is also critical.

1.2 THE WOUND HEALING PROCESS

(1) Haemostasis - The first phase of wound healing is haemostasis; during this phase, the body attempts to stop the bleeding associated with your wound. The platelets clump together at the injury site to form a clot to minimize blood loss. This clot acts as a temporary closure to the wound until a stronger and more durable scar tissue can develop later in the healing process. Haemostasis must be performed appropriately to prevent too much blood loss and help promote the following stages of healing.

(2) Inflammation - The second stage of wound healing is known as inflammation and occurs just after injury occurs and continues for a few days. After an injury occurs, the immune system sends white blood cells to the injured area to help fight off infection and clean out any foreign materials that are in the wound. This activity contributes to swelling, redness, and increased sensitivity of the injured area. Although inflammation is a normal portion of the healing process; excessive amounts of inflammation may hinder the healing process.

(3) Proliferation of Wounds

During this phase of healing, the body creates new tissue at the site of injury. New blood vessels are formed as granulation occurs. Granulation tissue is made up of a special type of protein called collagen, which is very important when it comes to healing a wound. The purpose of this protein is to give a supportive structure for new skin cells to grow and close up the wound. Proliferation happens usually between days 3 and 10 after an injury and can last anywhere from weeks to months, depending on the size and depth of the wound.

(4) Remodelling of Wounds

The last stage of wound healing is remodelling, which is when the body makes improvements to the tissue created in the previous stage. Collagen in new tissue is also reorganised during this time in order to make the healed wound stronger and look better than it did before being injured. The remodelling phase can last from several months up to years and the amount of strength added to the healed wound increases gradually throughout this period.

2.0 BIOLOGY OF WOUND HEALING AND CLINICAL REQUIREMENTSS

Haemostasis is the first stage of wound healing, during which a fibrin clot is formed from the aggregation of platelets to prevent blood loss. Following haemostasis, neutrophils and macrophages migrate into the wound during the inflammatory phase to remove pathogens and debris from the area. In the proliferative phase, the fibroblasts produce collagen and other components of the ECM while angiogenesis occurs to provide nutrients needed for the regeneration of tissue. In the final remodelling phase, the collagen fibres are reorganized to restore tensile strength of the tissue. Chronic wounds become chronic because they are held up during the inflammatory phase due to persistent infection, oxidative stress, and dysfunction in cellular signalling. Therefore, an ideal wound dressing should maintain a moist environment, be permeable to oxygen, absorb excess exudate, and prevent microbial colonization in addition to supporting cellular proliferation. It should also be non-toxic, non-immunogenic, biodegradable, and capable of sterilization without losing its function. Electro spun nanofibers meet these requirements in many ways due to their large surface area-to-volume ratio, interconnected porosity, and structural similarity to natural ECM fibres like collagen and elastin.

2.1 FUNDAMENTALS OF ELECTROSPINNING TECHNOLOGY.

Electrospinning produces ultrafine fibres using electric fields to make fibres from either a solution (solvent with a dissolved polymer) or a polymer melt. An electro spin operation consists of an electrically charged high voltage power supply, a polymer filled syringe with a metallic needle and a ground collector plate at a specified distance from the needle. The electric field force supplied by the high voltage source overcomes the droplet's surface tension, creating a Taylor cone at the tip of the droplet. The electric field also forms a path for the charged jet stream of polymer to the ground collector plate. As the jet travels to a collector, evaporation and extension of the solvent cause it to form a series of elongated nanofibers with diameters in the range of 10-100+ nm. The morphology and diameter can be affected by many factors including polymer concentration, molecular weight, evaporation rate, electrical potential applied during electrospinning, flow rate, tip-distance from collector, relative humidity, and temperature of the environment. Variants of electrospinning, including coaxial electrospinning, emulsion electrospinning, and needleless electrospinning are used as methods to produce core-shell structures and multi-layered scaffolds resulting in sophisticated biomedical applications. Electrospinning offers good ease of operation, scalability, and versatility for manufacturing wound dressings.

2.2 BIOPOLYMERS FOR ELECTROSPUN WOUND HEALING SCAFFOLDS

Biopolymers, as an alternative to synthetics, have become more desirable in the field of wound healing because they have a structure similar to that of a biological macromolecule, thus making them biocompatible. Some important examples would include; collagens, gelatine, chitosan, alginates, hyaluronic acid, and silk fibroin; each of which exhibit excellent cellular interactions and are biocompatible and bioactive. Chitosan contains polycationic properties making it naturally antimicrobial and therefore can disrupt the bacterial cell membrane. Collagen and gelatine have been shown to promote cell attachment and proliferation by presenting attachment (integrin) binding sites. Alginates have superior exudate (fluid) absorption and gel forming properties; therefore, can be used for highly exuding wounds. Silk fibroin offers outstanding mechanical strength and slow biodegradability.

In addition, microbial biopolymers have become a viable source for wound care as well. Polyhydroxybutyrate (PHB) is an example of a microbial biopolymer; it belongs to the polyhydroxyalkanoate (PHA) family and is produced by bacteria (ex. Bacillus subtilis). PHB has been shown to possess good mechanical strength, controlled biodegradability, and biocompatibility; therefore, PHB is being evaluated for use in scaffold development. However, PHB is often brittle and needs to be blended with another polymer to provide increased flexibility. There are many biodegradable synthetic polymers available in the market (PLA, PCL, PLGA) that can be blended with natural biopolymers in order to improve mechanical stability while maintaining their biological function. These blends can provide a system that optimizes the tensile strength, degradation rate and cellular interaction.

2.3 FABRICATION AND FUNCTIONALIZATION

In creating biopolymeric nanofibrous dressings, a polymer is typically first dissolved in an appropriate solvency and then produced through selectable electrospinning schemes to produce a web of nanofibers that simulate the desired alignment of their respective fibres when placed on a static or rotating collection medium. For fibrous scaffolding used for wound healing, fibre sizes will normally fall between 100 to 500 (nanometres), closely resembling the size/shape of collagen fibrils found in any tissue in its natural or physiologic environment. Potential methods of functionalizing these scaffolds include incorporating agents (e.g. gold nanoparticles), growth factors, anti-inflammatory medications, and herbal extracts into the nanofibers themselves. Homogenously distributing any medicated agent through a scaffold using electro spun blends/electrospinning techniques, or via creating a “Core-Group” arrangement with coaxially electro spun scaffolds would allow a prolonged (sustained) release of the attached medicinal agent into the now-available cells for tissue repair. Furthermore, various surface-modification processes (e.g. plasma treatment or chemical cross-linking) may provide increased stability of the electro spun scaffold while increasing their hydrophilicity. Therefore, constructing scaffolds using various techniques to attain selective control over porosity and fibre orientation is critical when influencing both cell migration and tissue regeneration processes 2.4 CHARACTERIZATION OF ELECTROSPUN NANOFIBERS

Characterization in detail is crucial when validating scaffold performance. Commonly morphological characterization is evaluated using scanning electron microscopy (SEM) in order to understand fibre uniformity and distribution based on diameter or fibre diameter variability due to multiple processes and their effects on scaffold structure. Chemical characterization can be completed with Fourier-transform infrared spectroscopy (FTIR) to confirm that functional groups within the fibre interact and X-ray diffraction (XRD) to measure crystallinity. Mechanical properties will be evaluated (i.e., tensile strength elated with elongation-to-break) to ensure scaffold durability during clinical handling and scaffold performance. Wettability testing will provide insight into a scaffold’s hydrophilicity, both of which will affect cell attachment and fluid absorption. In vitro degradation testing is performed under physiologic conditions to measure the mass loss of the scaffold and maintain certain properties of the scaffold during the degradation process to assess potential lifespan. Biological assessment of scaffold materials includes cytotoxicity testing (using for example, the MTT Assay), assessing their effectiveness in preventing the growth of bacteria commonly associated with wounds, and cell proliferation tests using either fibroblasts or keratinocytes. The in vivo portion of the characterization will be done through the use of an animal wound model to evaluate the ability of the scaffold to promote tissue regeneration efficiency (via collagen deposition) and the inflammatory response associated with implantation

2.5 ADVANTAGES OF NANOFIBROUS BIOPOLYMER DRESSINGS.

Compared to traditional dressing materials, electro spun nanofibrous dressings have numerous beneficial properties. Because of their high porosity, they provide good gas exchange and inhibit microbial contamination. Due to their ability to mimic the structure of the ECM, cells can adhere to them and proliferate. The ability to control how quickly the dressing degrades means that there is no longer any need for

painful dressing changes. In addition, drug-loaded nanofibers allow for the localized and extended delivery of therapeutic agents with minimal systemic side effects. In addition, the addition of antioxidants or plant-derived bioactive substances may reduce the amount of oxidative stress occurring in wounds. Collectively, these numerous beneficial features of electro spun nanofibrous dressings will help promote faster healing times and decrease the amount of scarring on the wound.

2.6 CHALLENGES AND LIMITATIONS.

Numerous obstacles impede clinical translation despite excellent potential results. Most natural biodegradable polymers have poor mechanical durability and fast degradation times. The toxicity of some of the solvents that are used, as well as residual traces from these solvents, may pose possible safety concerns. Scaling up electrospinning for industrial production is extremely challenging due to the high variability within batches and their sensitivity to environmental conditions. Processing methods (e.g., gamma radiation) used to sterilize medical devices may change the properties of the polymeric materials used to fabricate the devices. The regulatory pathway requires extensive validation through pre-clinical and clinical trials before moving forward with clinical studies. Solutions to these obstacles include the use of green solvent systems, optimization of cross-linking, and development of advanced manufacturing technologies prior to commercial use.

2.7 EMERGING TRENDS AND FUTURE PERSPECTIVES

Currently, there is an increasing trend in creating smart dressings for wounds that can react to temperature, pH, or the presence of infection biomarkers. The addition of nanotechnology to regenerative medicine has resulted in the creation of scaffolds, which are able to bind and release growth factors as well as provide a supportive matrix for stem cells to attach and grow in. Through the use of electrospinning techniques (three-dimensional) and portable electrospinning devices, there is currently a strong interest in developing methods for creating scaffolds at point-of-care sites. The use of new biopolymers and nanocomposite technologies will help significantly improve the mechanical properties and biological activity of new scaffold products. It is necessary for future research to prioritize scaling up production and developing environmentally sustainable production processes and developing appropriately designed clinical trials, which will help bridge the gap between laboratory research and clinical application.

3.1 CONCLUSION

Electrospinning is an innovative method for producing biopolymer materials to use in treating advanced wound care products. Combining nano-biomimetic structure and biodegradability with multiple therapies makes electro spun nanofibers a superior choice when compared to standard dressing fabrics for use in advanced wound care products. To make these products available as practical, low-cost solutions for wound healing, further collaboration between materials scientists, microbiologists, biomedical engineers, and clinicians will be required across disciplines.

4. REFERENCES

- W. Pan *et al.*Facile formation of injectable quaternized chitosan/tannic acid hydrogels with antibacterial and ROS scavenging capabilities for diabetic wound healing. Int. J. Biol. Macromol. (2022)
- K. Liu *et al* .A lignocellulose-based nanocomposite hydrogel with pH-sensitive and potent antibacterial activity for wound healing. Int. J. Biol. Macromol (2021)
- A. Grada *et al.* Research techniques made simple: analysis of collective cell migration using the wound healing assay. Investing. Dermatol. (2017)
- F. Song *et al.* A robust regenerated cellulose-based dual stimuli-responsive hydrogel as an intelligent switch for controlled drug delivery. Int J. Biol. Macromol.(2021)
- S.G. Park *et al.* Thermosensitive gallic acid-conjugated hexanoyl glycol chitosan as a novel wound healing biomaterial Carbohydrate Polymers(2021)
- X. Yang *et al.* Collagen-alginate as bioink for three-dimensional (3D) cell printing based cartilage tissue engineering Mater. Sci. Eng. C (2018)
- X. Qi *et al.* ε-polyline -stabilized agarose/polydopamine hydrogel dressings with robust photothermal property for wound healing Carbohydras. Polymer. (2021)