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ADVANCED WOUND DRESSINGS: A COMPREHENSIVE REVIEW OF MATERIALS, PROPERTIES, AND CLINICAL APPLICATIONS

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ABSTRACT

Healing from wounds has always been extremely difficult throughout human history. Nowadays, there is a greater need for wound dressings to speed up the healing process due to a significant increase in chronic illnesses and surgical procedures. Modern dressings are available in a variety of forms and, by blocking microbial activity and keeping the wound appropriately wet, provide a number of benefits over passive bandages, which have been in use for a long time. Even current dressings, with their extensive clinical use and effective results in treating wounds, cannot promote wound healing as predicted since they are not responsive to the circumstances of the wounds. Dressing plays an important role in creating a standard for wound care and its management a) Enabling a protective physical barrier, b) absorbing wound drainage and c) helps maintaining suitable moisture range for promoting epithelial layer recovery. The choice of dressing material greatly varies depending on the type of anatomical and pathological features of the wound inflicted. Contemporary wound dressing practices offers enhanced perks over outdated dressings such as anti-microbial and pain management. Moreover, this review explores the fundamental principles of wound dressing, outlines the key features of both introductory and complex dressing types, and provides practical guidance for their selection and application.

KEYWORDS: Regeneration, Healing, Wound, Dressings, Hydrogel, Antimicrobial.

INTRODUCTION

Wound dressings have witnessed an evolutionary process from organic material that majorly focuses on covering and protecting the wound by acting as a concealed barrier, to materials that target on management of moisture, and more recently, the materials that deliver active pharmaceutical ingredient or interact with cells or some specific chemicals applied locally on wound environment.[1]

The wound or ruptured tissue is filled with blood clots, followed by acute inflammation at the site of surrounding tissue. The discharge of inflammatory mediators and inflammatory cells causes swelling, redness, and pain. Fibroblasts, endothelial cells, and newly formed capillaries interact to form a new tissue layer at the site of the wound.[2]

The most suitable wound dressings should be non-sticky and removes secretion while maintaining a moist environment for efficient healing. An ideal wound dressing prevents bacterial infection and formation of biofilm, does not affect healing, and promotes healing without any scar formation.[3]

The wounds can be classified into chronic and acute wounds. As for acute wounds, the injury could be conceived by various stimuli, such as radiation, temperature changes, or contact with toxic chemicals. This type of wound generally heals in 8 to 12 weeks. On the adjacent side, chronic wounds take a longer period to heal (even a few months), due to prolonged inflammation. Chronic wounds can result from various causes like infection, physical agents, and tumours.[4]

The most commonly used modern dressing in the healthcare industry are hydrogels, hydrocolloids, alginates, foams and films. Hydrogels are hydrophilic polymers which can subsequently absorb water, hydrogels have excellent moisturizing capability and also maintain the moist environment around wounds, and facilitate an impactful role in cleansing necrotic tissue. In addition, a wound covered in hydrogel dressings has an advantage because they are typically transparent, Hydrogel are mostly used in pressure ulcers, surgical wounds, burns, radiation, and dermatitis.[2]

Hydrocolloid dressings are advance wound care product, they encourage moist healing environment and offer defense against impurities and germs. Hydrocolloids absorb moderate amount amounts of wound exudate, forming a gel that helps in maintaining optimal moisture levels.[5] Alginate-based wound dressing materials is made up of different types of biopolymers. The functional group of alginates can be easily blended with other biopolymers hence forming cross-linked network to provide a moist environment.[6] Foam dressing facilitates transport of the exudate into the foam and comes in contact with wounded skin.[7] Films are extremely versatile dressing types that can be used in the treatment of topical wounds such as surgical burns, surgical wounds, and skin grafts. Film dressings make an optimal moist environment locally to promote healing and act as a barrier to bacteria.[8] Antimicrobial embedded dressing can be useful in the wound that are topically infected or may have chance for topical infection. For non-healing wound that need more growth activation, tissue-engineered dressings have become a feasible option in the past few years.[9]

MARKET VALUE: Wounds are a worldwide medical issue. The global wound care market is expected to exceed $22 billion by the end of 2024. The growth is primarily driven by an increase in road accidents, the prevalence of chronic diseases like diabetes, and the growing elderly population.[10] The world's wound dressing marketplace is projected to grow at 4.14% from 2024 to 2030.[11]

Wound dressing is an essential area of the healthcare industry with its economic value at approximately $ 22 billion (in 2024) in the global market. According to recent clinical trials the use of modern dressings can be most accessible, economic and the easiest way to treat chronic wounds.[12] A retrospective analysis of the available data estimated that (medicare costs for all wounds ranged from $28.1 billion to $96.8 billion, including costs for infection management) However, the actual value of wound dressing remains unknown among the worldwide population.[13]

BIOCHEMICAL PROCESSES OF WOUND HEALING: On the basis of pathogenesis and biochemical processes the wound healing is further classified as Acute Wound Healing and Chronic Wound Healing. Acute wounds go through a bunch of molecular events that eventually progress in the regaining of structural integrity. On the other hand, chronic wounds fail to resolve and are classified by pathological processes, such as inflammation, proliferation, infections and necrosis.[14]

MECHANISM OF WOUND HEALING: Typically, the process of mammalian wound healing is categorized into four concurrent phases: hemostasis, inflammation, proliferation, and remodeling.[15]

HEMOSTASIS PHASE: Burns cause the surrounding tissue to become significantly devascularized, and they spread centrifugally from the injury site through the stasis zone. This leads to an increase in vascular permeability and a decrease in oxygenation. The haemostasis phase starts reparative healing. Shortly after a cutaneous injury, the process starts to form a blood clot consisting of platelets, cross-linked fibrin, and fibronectin. Early clotting prevents excessive bleeding and contributes to protecting the wound from infection. The clot may further act as a provisional ECM (extracellular matrix), which is able to stock the growth factors and provide the migratory drive on vascular cells, leukocytes, and fibroblasts in the inflammatory phase. In early embryos, hemostasis is initiated by the formation of a fibronectin clot. Fibrin is absent in the clot, and platelets have not yet matured. Further, re-epithelialization begins right away and proceeds quickly. Besides this, it also releases various mediators of wound healing, like (PDGF) platelet-derived growth factor and transforming growth factor beta (TGF-βeta), that trigger the inflammatory response.[16-17]

INFLAMMATORY PHASE

In this phase the synthesis of different cytokines, the release of chemokines, and numerous other factors begins, that impact immune responses.[18] After hemostasis, the inflammatory phase begins. Some immune cells minimize the injury and act as a barrier against microorganisms. At this phase, leukocytes are attracted at the site of injury to phagocytose-entered bacteria, and foreign debris. For this, neutrophils release proinflammatory cytokines that act as a response to inflammation, promoting the expression of adhesion molecules in order to phagocytose the entered bacteria and foreign debris by mainly neutrophils. Meanwhile, monocytes transmigrate into the wound area and begin differentiation into macrophages. These cells can attract further monocytes and enhance their response. Neutrophils, monocytes, and macrophages are involved in this phase because of the release of mediators, including proinflammatory cytokines such as interleukins (IL-1, IL-6, IL-8, and tumour necrosis factor α, TNF-α), and growth factors such as PDGF, TGF-α, TGF-β, fibroblast growth factor (FGF), insulin like growth factor 1(IGF-1), enables the activation of fibroblasts and epithelial cells required for the next phase.[19] Beside this PDGF is the most widely released factor, the migration of fibroblasts to wound is dependent on it, and its local signalling effect on fibroblasts cannot be understated.[17]

PROLIFERATIVE PHASE

As the inflammatory phase ends, the proliferative phase starts.[17] The proliferative phase of wound healing is distinguished by the extreme migration, spreading of cells, and formation of granulation tissue, consisting of macrophages, endothelial cells, ECM, and fibroblasts. The damaged cells then release FGF, VEGF, EGF (epidermal growth factor), and TGF-βeta1 (transforming growth factor-βeta1), to start the multiplication of (fibroblasts, keratinocytes, and endothelial cells). Fibroblasts also synthesize provisional extracellular matrix (ECM) compounds, type III collagen, proteoglycans, and fibronectin, which support cell migration into the area. The restructuring of vascular networks in the wound starts instantly after injury, although it has increased activity in this phase, providing oxygen (O2) and nutrients needed in the process of cell migration, spreading, and synthesis of extracellular matrix (ECM) compounds. Secreted mediators, like VEGF and angiopoietins, act on the proliferation of endothelial cells and the restructuring of vascular systems at the wound site. During the proliferative phase, reepithelialization takes place, which closes the epithelial gap and hence re-establishes the skin barrier. First, growth factors stimulate the keratinocytes located at the border of wounds, leading to their proliferation and differentiation. This stimulus causes the loss of adhesion molecules in keratinocytes, thus blocking their direct physical contact with desmosomes and hemidesmosomes, and increasing the rate of migration of such cells through the extracellular matrix (ECM).[20]

REMODELLING PHASE (MATURATION PHASE)

The remodeling phase (also known as the maturation phase) is the lengthiest phase of wound healing and is reliant on a fragile equilibrium between synthesis and degradation.[8] Subsequent to synthesis of the extracellular matrix, the last phase of wound healing starts, which is the most elongated process after the process of re-epithelialization. It initiates at the end of granulation tissue development. The time interval of remodeling phase is about 21 days until one year post wounding. Myofibroblasts are responsible for contraction of wound during remodeling phase. Fibroblasts cells convert into myofibroblasts. Extracellular matrix made by the fibroblasts which offers a framework for cell migration, proliferation also promote textile strength of wound.[9] collagen III forms the majority of granulation tissue, which is slowly substituted by the more potent collagen I as the wound heals. This takes place due to parallel collagen I formation and collagen III lysis, followed by ECM remodeling. In the remodeling phase, depending on the anatomy and physiology of the wound and measures taken for its treatment, scar tissues are formed which might take several months or even years to complete[10] After the remodeling phase, wound tissues closely resemble as normal tissue. The remodeling phase focuses on restoring the structure and function of the tissue. In this phase, changes in the composition and structure of the extracellular matrix (ECM) enhance the tensile strength of the tissue. The healed wound reaches approximately 80% of the tensile strength of normal skin as collagen type III which is gradually replaced by type I, boosting the tissue's strength to near-normal levels. Fibroblasts and other cell produce matrix metalloproteinases, enzymes that degrade the (ECM) and are important for wound repair. Excessive cell proliferation can lead to scarring. Sometimes the entire area of a wound is not completely covered with epithelial tissue, forming a scar that is concentrated fibroblasts that may impede function of the organ.[9]

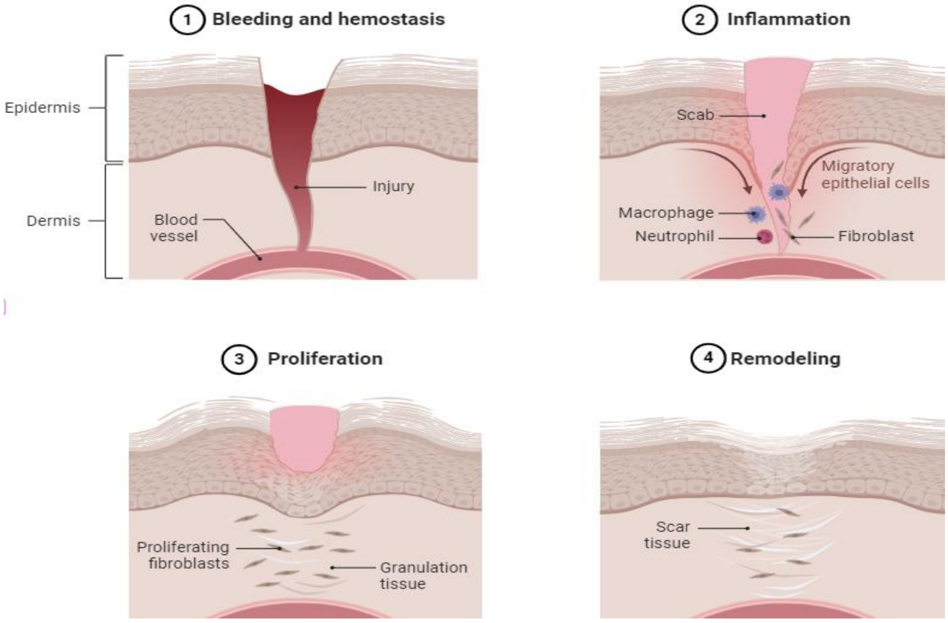

Fig. 1: Pathogenesis of wound healing [created from bio render].

CHALLENGES IN WOUND HEALING

In excess of the overwhelming majority of the chronic wounds suffers from bacterial contamination and further biofilm formation which leads to the problems during treatment, and also due to the presence of increased number of inflammatory cells and pro-inflammatory cytokines production a bacterial infection is very common.[24] There are various challenges in the process of wound healing such as mechanical challenges, ischemic challenges, malnutrition challenges, infectious tissue challenges, oxidative challenges, disease challenges, inflammatory challenges.

Ischemic challenges can occur by creating hypoxia (lack of oxygen) that plays vital role in the stimulus of fibroblast growth and angiogenesis, which causes malnutrition of wound tissues.[25] Malnutrition challenges can impede wound healing by prolonging inflammation and disrupting essential processes such as angiogenesis, phagocytosis, fibroblast metabolism, and ECM remodeling. Proteins and amino acids (like arginine, cysteine, methionine, and glutamine) play a crucial role in regulating immune cell activity and collagen production. Additionally, iron is a cofactor in collagen synthesis and is vital for effective wound repair.[20] Micronutrients' antioxidant properties also play an important role in the process of healing of wound.[26] Mechanical challenges can occur due to trouble in retaining locally delivered medications during regular movements or change of dressing. Mechanical challenges in wound healing are crucial because physical forces and tissue mechanics plays significant roles in healing process. Patch delivery or bandage based protected delivery can be used in the case of mechanical challenges in wound healing.

Oxidative challenges can occur due to free radical produced by unregulated oxidative stress, these free radicals can cause cellular damage and death. Chronic inflammation is followed by increased ROS synthesis resulting in tissue damage. Deferoxamine and other free radical hunter have been shown to decrease oxidative stress in wounds. Infected/necrotic tissues challenges can occur due to chronic inflammation on the infected tissue, which aborts the phases of healing. Necrotic tissues lack the ability to heal and is prone to infection.[27]

Chronic disease challenges can occur due to complications like diabetes or peripheral vascular disease which effects immune response and circulation, resulting in delayed healing.[28] Chronic inflammation challenges can cause delay in the healing process and aborts proper tissue repair.[29]

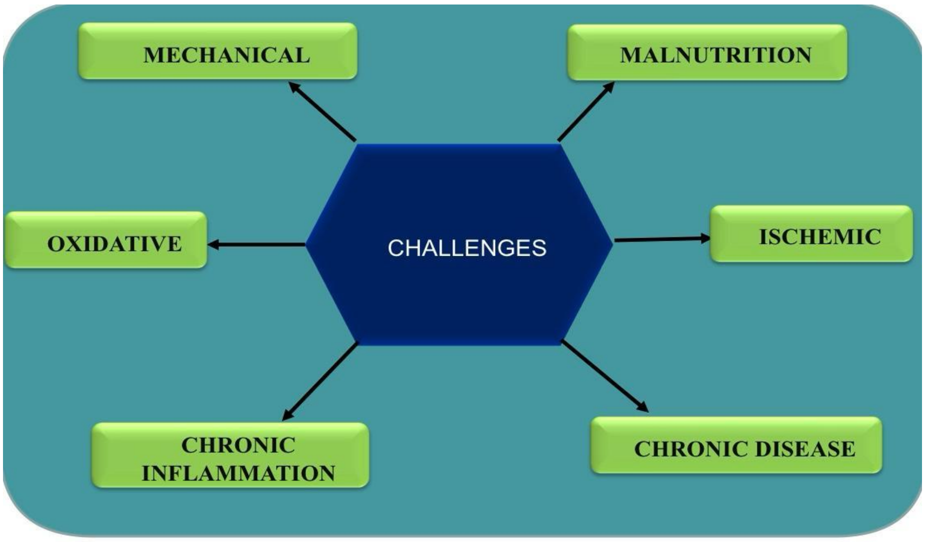

Fig. 2: Typical Challenges in Wound Healing Process.

IDEAL PROPERTIES OF WOUND DRESSINGS

1) Ideal properties of wound dressings should be easy to apply, maintains pleasing environment, economical, non-allergenic and maintain moist environment.[30]
2) A moist environment of the wound has various advantages that result in better quality of healing. Moist wound environment facilitates autolytic debridement, reduces pain, and scarring. Wound dressings can be utilized to create, maintain, and control moisture for healing.
3) Wound dressing should provide a moist environment and have an optimal absorbance capacity, and it should also protect the wound against trauma and contamination.[31]
4) Wound dressing should not just focus on drainage of the wound but must also retain vapour and air circulation around the wound including adequate microclimatic conditions to promote healing process.
5) Modern-day dressings have an enhanced level of certain requirements, which circles to the recent developments aiding in sophistication and ease in use of medicinal technology, the necessity for enhancing the efficacy of the first aid and post-surgical repair, and the increased level of visual appeal.[32]
6) Wet dressings can speed up the wound healing process more effectively than dry dressing. In fact, new skin can regenerate without inflammation or scar formation only in moist environment. Therefore, wet dressings are considered ideal for wound care.[33]
7) Ideal wound dressings must provide debridement action to increase leucocytes transfer and support the accumulation of enzyme, wound dressing should be sterile, non-toxic, and non-allergic to wound environment.[34]
8) An ideal wound dressing requires ample amount of energy for supporting wound healing process. In

case of a reduction of energy production, the wound healing process could be significantly delayed or in severe cases, halted altogether, also can poses extremely serious risks for the patients. The disruption of skin tissues and blood vessels at the wounded sites causes depletion of oxygen, resulting in local hypoxia.[35]

9) Future directions of an ideal wound dressings are that it can integrate numerous functions like monitoring, anti-microbial effect, pain relief, immune modulation, and regeneration, which can help in effective wound repair and regeneration.[36]

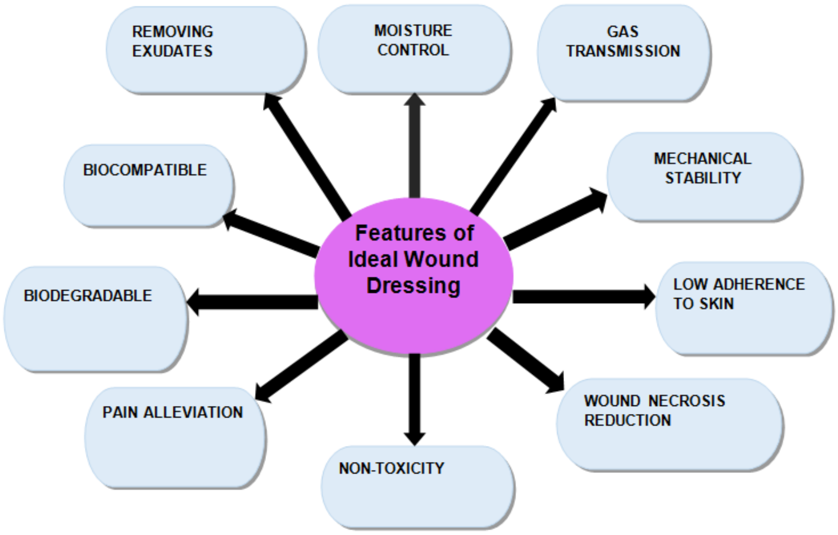

Fig. 3: Key Characteristics of an Ideal Wound Dressing.

Types of Wound Dressings

1. Gauze Dressings

Since 1891, Johnson & Johnson has been mass-producing gauze dressings, which are the most popular and well-known type of wound dressing. They are made by sterilizing cotton yarn and thread. The fibers that make up gauge are either woven or non-woven cotton, rayon, or polyester. Woven gauze has a loose weave that facilitates the wicking and absorption of fluids and wound exudate.

It is frequently used as a primary dressing or to cover additional dressings and offers a barrier against pollutants. There are many mesh sizes for woven gauze; fine gauze works better for packing wounds, while coarse gauze is helpful for debriding wounds.[37]

Synthetic strands such as polyester or rayon are pressed together instead of woven to create non-woven gauze. Compared to woven gauze, this enhances its absorbency, strength, mass, and reduces the likelihood of lint remaining in the wound. Small cuts and abrasions are frequently treated using non-woven gauze as the initial bandage.

Whether applied to big or irregularly shaped wounds, infected or non-infected, or as packing to regulate exudate or prevent premature wound closure, gauze dressings are dependable, priced, and extremely absorbent. Wet-to-dry gauze dressings, on the other hand, have been widely used for mechanical debridement, but they might potentially delay healing and cause stress to the wound when removed.

2. Foam dressing

Foam dressing were first introduced in (late 1970s and early 1980s) Silicone foam or hydrophilic polyurethane make up foam dressings. They offer insulation and are absorbent. Pressure ulcers and diabetic foot ulcers are examples of moderate-to-heavily exuding lesions that are best treated with foam dressings. To aid in the healing process, they cushion, absorb exudate, and keep the wound moist. On the other hand, foam dressings can be more costly than gauze and may not stick as well to dry wounds.[38]

3. Hydrogel dressing

Hydrogels are water-based, amorphous, clear, or transparent dressings that provide moisture to the wound. They are composed of a three-dimensional network of hydrophilic polymers. Hydrogels are suitable for dry, sloughy, or necrotic wounds as they help rehydrate the wound bed and facilitate autolytic debridement. They promote a moist healing environment which can reduce pain and enhance healing. However, hydrogels are not suitable for heavily exudating wounds as they can become saturated quickly.[39]

4. Alginate dressing

Alginates are dressings made from brown seaweed that are extremely absorbent. They are made up of alginic acid salts with calcium and sodium content. For extensively exuding wounds, such as surgical wounds and venous ulcers, alginate dressings are perfect. They have haemostatic qualities, absorb exudate, and gel when in contact with wound fluid to keep the area wet. Alginates, however, are not appropriate for dry wounds and need a moderate to high degree of exudate in order to work effectively. Area wet. Alginates, however, are not appropriate for dry wounds and need a moderate to high degree of exudate to work effectively.[40]

5. Film dressing

Film dressings are semi-permeable, thin, translucent polyurethane membranes that are adhesive on one side. They provide visibility of the wound, maintain a moist wound environment, and function as a bacterial barrier. Examples of superficial wounds with minimal exudate that respond well to film dressings are adhesions and IV sites. They may not be suitable for wounds that ooze a lot, though, because they are not absorbent.[41]

6. Hydro-fiber dressing

The material used to create hydro Fibers, sodium carboxymethylcellulose, has a high capacity for absorption and may store 25–30 times its weight in fluids. When hydrofibers encounter wound exudate, they form a gel that retains moisture in the wound environment. Because they are quite absorbent, they are effective for wounds that exude mildly to. Aquacel is a well-liked hydrofiber dressing.[42]

7. Composite dressing

Composite dressings are treatments that include two or more types of dressings into one. They are made to be bacterial barriers in addition to being absorbent. Composite dressings are adaptable and can be customized to meet certain wound requirements. However, because of their intricacy, application and usage may become unclear.[43]

8. Chitosan dressing

Chitosan is the most plentiful natural polymer and is greatly expected to be a valuable resource for the preparation of anti-microbial agents. Chitosan is biodegradable and non-toxic and has the effect of facilitating the wound healing; therefore, it can be chosen as a starting material for the wound dressings. As seen in the figure above, chitosan monomers have a single amino acid structure other than being the only alkaline polysaccharides and possessing a positive charge under acidic conditions, it can inhibit most bacteria. The attractiveness of a chitosan-based dressing is first, easy to synthesize second, the incidence of adverse reactions in minor and third, no require for additional anti-bacterial additives.

To enhance its Future use and demand, functional modification of chitosan has been done using cationic agents such as amines, pyridines, imidazoles, quaternary ammonium salts and guanidine.[44]

ANTI-MICROBIAL WOUND DRESSING MATERIAL

By adding ingredients that inhibit microbial growth, antimicrobial wound dressings are crucial for treating wounds that are prone to infection or are showing symptoms of infection. These dressings, which come in combinations with iodine, silver, and honey, are selected for their efficacy in various clinical situations. Because of its broad-spectrum antibacterial effectiveness against bacteria, fungi, and some viruses, silver is employed extensively. Silver dressings are useful for treating chronic wounds like diabetic ulcers and pressure sores because they help manage bioburden and lower the risk of infection. They come in different forms, including gels, foams, and impregnated gauze.[45] Honey is prized for its inherent antibacterial qualities, which come from its production of hydrogen peroxide, low pH, and high osmolarity. This is especially true of medical-grade Manuka honey.

Because of this, honey dressings work well for debriding wounds and preserving moisture, both of which are essential for healing, particularly in the case of burns and chronic ulcers.[46] Broad-spectrum, iodine-based dressings, such as those containing iodine complexes or povidone-iodine, exhibit strong antibacterial action against a variety of infections. They work well for wounds that are infected or have a high risk of infection, but they should be closely watched because they might irritate or discolor the wound.[47] Cadexomer iodine, which is encapsulated in a starch matrix, offers both antimicrobial protection and fluid absorption, making it effective for controlling wounds with moderate to high exudate.[48] To offer a comprehensive approach to infection prevention and healing, advanced dressings frequently combine silver with honey, especially for chronic wounds.[45,46]

Several criteria, such as the nature and state of the wound, patient sensitivities, and financial concerns, influence the choice of antimicrobial dressing. For example, hydrocolloid dressings that have been infused with antimicrobial agents work well for wounds that have low to moderate exudate because they create a gel-like layer that keeps the wound wet and provides antibacterial protection. Similar to this, extremely absorbent foam dressings with antibacterial qualities are appropriate for wounds with moderate to high exudate.[49] Alginate dressings are made from seaweed and treated with substances like iodine or silver. They combine fluid management and antibacterial activity, making them extremely absorbent and useful for wounds with a lot of exudates. The type of wound, amount of exudate, patient allergies, and cost must all be considered when selecting an antimicrobial dressing. Some advanced dressings provide prolonged antibacterial action, which lowers the need for dressing changes. Comprehending these variables guarantees efficient management of infections and facilitates ideal wound healing.[6]

Table 1

TYPES	PROPERTIES	USES
SILVER-BASED	● Effective against bacteria and fungi ● Found in gels, foams and impregnated gauze.	Ideal for chronic wounds like pressure diabetic ulcers
HONEY-BASED	● Natural antimicrobial properties. ● Supports moisture retention and debridement.	Useful for burns and chronic wounds.
IODINE-BASED	● Broad spectrum protection but requires monitoring. ● Strong antibacterial action but may cause irritation or discoloration	Suitable for a variety of infections, but needs caution in sensitive applications.

NANOMATERIALS-BASED WOUND DRESSING

Nanomaterials-based wound dressings are at the interface between modern medical science and clinical practice that are revolutionizing how we treat wounds. These dressings use nanomaterials-materials that have a structure between 1 to 100 nanometers in at least one dimension of their physical state, with distinctive physio-chemical properties differing significantly from those bulk materials.[50] A major example is silver nanoparticles that have broad-spectrum antimicrobial characteristics. Silver nanoparticles are effective antimicrobials able to fight against a wide spectrum of pathogenic bacteria and fungi, making them ideal for the treatment or prevention of infections in both acute wounds (surgical wounds) usually occurs outside (hospital-acquired infection), and chronic wounds. Due to their size, one popular idea is they have better access to microbial cells — making it possible for them in more quickly and efficiently way interact with others.[51]

Nanofibers which is another type of nanomaterial helps develop scaffolds required for a replica of the extracellular matrix that is significant in cell migration, proliferation, and tissue formation. Such nanofiber-based dressings can be fabricated from electrospinning, a technique that forms fine nonwoven fibrous structures with high porosity and biocompatibility and good mechanical properties. These aspects may include large surface area of the nanofiber that helps them to come into closer contact with the affected tissues hence enhancing the healing process. PCL and chitosan are preferred in fabrication of these nanofibers for their properties like biodegradability, non-toxicity and others.[52]

The new generation of stiff dressings involves incorporation of nanoparticles into the traditional polymers, creating an improved and synergistic structure to the dressings in terms of mechanical and biological performances. For instance, when the nanoparticles are incorporated into the polymer matrix the resultant material would exhibit enhanced mechanical properties, flexibility, and moisture absorption characteristics which are vital in order to create the right atmosphere for wound healing. Some nanocomposites also enclose therapeutic agents which can be delivered gradually and can directly apply treatment to the wounded area.[53]

The properties associated with nanomaterials-based dressings also include the fact that they meet complicated wound care requirements. For instance, conditions such as diabetic ulcers or pressure ulcers for example are known to have chronic wounds that are characterized by slow healing due to inflammation or infection. Nanomaterials can be designed to deliver anti-inflammatory drugs or growth factors gradually allowing a decrease in inflammation and an increase in tissue repair. This controlled release feature means that therapeutic agents are released at the right place and in the right time hence enhancing the effectiveness of the treatment.[54]

Nevertheless, there is a concern with the application of nanomaterial into wound dressing. This is due to the fact that long-term impacts of these nanomaterials on human beings have not been ascertained. Research must also close off the possibilities of these materials yielding toxic or allergic consequences. Another big factor has to do with the regulation of the same where nanomaterials have to undergo rigorous tests of safety and efficiency before being used clinically. In addition, the high cost of production of nanomaterials and difficulties in moving from small-scale production to industrial scale may be a challenge which may retard the widespread use of the nanomaterials.[55]

Prospectively, there exists the prospect on installing techniques that include smart technologies into dressings based on Nanomaterials. Such ‘smart’ dressings can be designed to include a system that records the status of the wound as it is; releases healing agents or even modifies characteristics as per environmental conditions. Further, creation of nanomaterials that are fully biodegradable would eliminate dangers since the working dressings would only biodegrade and be safe for the environment.[56]

Taken together, the defined nanomaterials featured and described to be incorporated in the wound dressings are revolutionary in wound management because of the multifunctional properties of nanomaterials as well as their ability to deliver therapeutics to the site of wound with a high degree of specificity. However, the advancement of these difficulties remains as focus of future studies; and as research progresses so the likelihood of overcoming these challenges and continuing to introduce these new dressings into clinical practice which harbor positive factors in enhancing patient benefits and helping to bring a change in practice within the area of wound healing.[57]

RECENT ADVANCES IN WOUND DRESSING

Smart wound dressings

Smart wound dressings play a vital role in wound care technology. These smart dressings consist of sensors and diagnostic tools which is present on the dressing material surface, influencing regular monitoring of the wound environment. By analyzing factors such as the temperature of a wound, PH levels, and moisture content, smart wound dressings provide real data that can be important for determining the wound conditions and the effectiveness of the treatment.[58] This technology not only manages wounds but also permits the early detection of major wound-related complications. Few smart dressings have been designed to carry alert systems that notify health specialists or patients about changes in dressing or when signs of infection are apparent, thus making care more responsive. The data gathered from these dressings can also be integrated into electronic health records, enabling personalized management of the wound.[59]

Biodegradable and Sustainable Options

As the environmental awareness is raising, a great substitution has been seen that biodegradable and sustainable wound dressings are being fabricated. Material innovations include natural polymers like chitosan, alginate and collagen— allowing not only the necessary benefits of wound care but also a more environmentally-sustainable approach.[60] It adds that the alcohol business also is turning to sustainable development practices, so there are more renewable resources on tap and less waste in manufacturing. These advancements offer a wide array of benefits, not only environmental; biodegradable wound dressing materials are designed to be eco-friendly and non-toxic as well — they might no longer cause allergies or skin symptoms.[61]

Customized dressings

Customization attending to each patient on an individual basis with tailored approaches and products is the current “calling-card” in wound care. The technology of material science has evolved to allow for dressings which are designed specifically according to the type and characteristics of a wound or for personalized treatment. Due to their distinct compositions, wound dressings can be specially designed to target different types of injuries - providing better treatment for diabetic ulcers compared to pressure sores or surgical wounds.[62] It is also about the size and shape of dressings; "one size fits all" does not apply properly to different sizes of wounds and anatomical sites. The focused application serves to enhance the treatment given to wounds effectively, enhance comfort, and improve patients' satisfaction with their care.[63]

CONCLUSION

Therefore, in this paper, the development of wound dressings has been noted, where formerly they were just a sort of shield, while today, they are the most effective materials that promote healing. Contemporary dressings like hydrogels, hydrocolloids, alginates, and nanomaterials have better features of water-holding capacity, anti-infective and healing properties as compared to conventional methods. These dressings not only control wound exudate and minimize chances of infection but also enhance the creation of a moist environment which is very important in the healing process.

The modern developments in smart wound dressings that include diagnostic features and biodegradable elements also illustrate the direction of the further development of individualized and environmentally friendly technologies for wound healing. More advanced nanomaterials like silver nanoparticles and nanofibers enhance the mechanical as well as biological properties of dressings making it possible to have controlled release of drugs.

It is important however to note that there are still barriers to adopting these technologies for advanced wound care among them being safety concerns, cost factors, and issues of scale. Nanomaterials have not been studied long enough to determine their effects on human health and their use in clinical practice is still hampered by issues of synthesis and governmental approval. In general, the technological developments in the wound dressing industry are likely to enhance patient satisfaction and to decrease patients’ treatment costs in the long run, as well as contribute to the demand for better wound healing management in view of the continuously increasing prevalence of chronic diseases and aging populations.

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