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Review Article

Advanced Wound Care Products: Mechanisms, Efficacy and Safety Considerations

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ABSTRACT

The market for advanced wound care products worldwide is valued at $7.1 billion, with an expected 8.3% annual growth rate, the $7.1 billion global market for advanced wound care products is expected to reach $12.5 billion by 2022-25. This market expansion underscores the increasing demand for innovative solutions to address the complexities of chronic and difficult-to-heal wounds. Despite significant advancements in wound care therapies, the intricate mechanisms underlying both normal and abnormal wound healing are not yet fully understood. Creating an optimal host environment is crucial for facilitating effective wound healing across its various phases. This paper explores advanced wound care products, mechanisms, efficacy and safety considerations, highlighting their critical role in improving patient outcomes. The study provides a comprehensive understanding of how modern wound care innovations contribute to enhanced clinical practices and patient care by analyzing these factors.

Keywords: Wound healing, Hydrophilic polymers, Gelatin, Cellulose, Bone Wax, Silicon Gel and Haemostasis.

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INTRODUCTION

Healing a wound is complex and involves several overlapping stages, including hemostasis and bleeding, inflammation, proliferation and remodeling. After an injury, the skin's tissue's ability to heal properly depends on completing these processes successfully. The initial stage of inflammation is triggered by the disruption of the skin's protective barrier, leading to the activation of the body's immune response. During this phase, various cell types, such as neutrophils and macrophages, are recruited to the site of injury, clearing away debris and initiating the healing process. The release of cytokines and growth factors during this stage stimulates the proliferative phase, where the damaged tissue's regeneration occurs. The formation of granulation tissue, angiogenesis and the re-epithelialization of the wound characterizes the proliferative stage. Endothelial cells and blood vessels begin to proliferate, facilitating the delivery of essential nutrients and oxygen to the wounded area.[1] Simultaneously, fibroblasts migrate to the site, secreting collagen and other extracellular matrix components, which provide the structural framework for the new tissue. The final stage of wound healing, known as remodeling, is a dynamic and intricate process that involves the reorganization and maturation of the newly formed tissue. During this stage, the extracellular matrix of the wounded tissue is reconstituted to be similar to healthy tissue, leading to wound closure and the formation of a new epidermal layer.[2-4] The remodeling phase is characterized by the differentiation of fibroblast cells into contractile myofibroblasts, which play a crucial role in tissue remodeling and wound closure. This process is facilitated by the movement of T-lymphocytes into the wound bed, which secrete biomolecules such as fibroblast growth factor VII, keratinocyte growth factors and insulin-like growth factor-1 to regulate fibroblast and keratinocyte expansion during this stage as shown in Figure 1.[3] The properties of several types of aquatic animals and their products have also been found to have a positive impact on the remodeling phase of wound healing.[5] However several parameters, including the wound Nature, the patient's health and the presence of long-term illnesses, can obstruct this process and result in chronic or non-healing wounds. In terms of treatment expenses and the impact that they have on patient's quality of life, chronic wounds followed as diabetic foot ulcers, pressure ulcers and venous leg ulcers pose a serious challenge to global healthcare systems. The treatment of these difficult wounds has changed dramatically with the introduction of proficient wound care solutions. In addition to protecting the wound, these products are made to actively aid in the healing process by creating an environment that is favorable to cellular activity, regulates exudate, lowers the risk of infection and encourages tissue regeneration. Due to their effectiveness in a variety of therapeutic situations, several products-hydrogels, absorbable gelatin sponges, oxidized regenerated cellulose, collagen wound

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dressings; silicone gel sheets and bone wax have become more well-known. With an emphasis on these advanced wound care treatments' mechanisms of action, clinical efficacy and safety profiles, this study attempts to offer a thorough examination of them. Healthcare professionals can choose the best treatment modalities for their patients by being informed about the benefits and drawbacks of each product. This evaluation will also look at new developments in wound care and the possibility of upcoming breakthroughs that could improve patient outcomes even further.

HYDROGELS: MECHANISMS, EFFICACY AND SAFETY

Hydrogels, composed of hydrophilic polymer networks, are known for their ability to retain large volumes of water, creating a moist wound environment that is critical for optimal healing outcomes. This moisture helps facilitate autolytic debridement, reduces pain and supports epithelial cell migration across the wound bed, promoting tissue regeneration.[6-10] By interacting with wound exudate, hydrogels can absorb excess fluid while maintaining a gel-like consistency, making them particularly beneficial for wounds with low to moderate exudate.[11] Furthermore, hydrogels can serve as carriers for therapeutic agents such as growth factors, antibiotics, or enzymes, allowing for sustained release over time and enhancing the healing process.[12]

Various hydrogel formulations are available to meet the specific needs of different wound types. Amorphous hydrogels, for instance, are free-flowing gels that can be applied directly to the wound, making them ideal for irregularly shaped wounds or cavities.[13] Pre-formed hydrogel sheets offer a simple application and are commonly used for superficial wounds with low exudate. Impregnated hydrogels, which are integrated with materials like gauze or foam, offer additional structural support and are often used in combination with other dressings to manage more complex wounds.[10]

Hydrogels have demonstrated significant efficacy in promoting wound healing across various clinical settings. A study involving patients with pressure ulcers revealed that hydrogel dressings considerably reduced wound size and facilitated faster healing compared to conventional dressings.[14] The moist environment provided by hydrogels encourages epithelial cell migration, thereby accelerating re-epithelialization of the wound surface.[15] Similarly, in patients with diabetic foot ulcers, hydrogels were shown to reduce overall healing time and improve patient comfort, particularly due to their cooling effect, which helps alleviate chronic wound pain.[16] For burn injuries, hydrogels have been proven especially effective, as they maintain a moist wound environment, relieve pain and allow for easy wound monitoring due to their transparency.[17]

Despite these benefits, hydrogels are less effective in managing heavily exudating wounds due to their limited absorption capacity. In such cases, hydrogels are typically combined with more absorbent dressings to ensure proper exudate management while maintaining the advantages of a moist wound environment.[10]

Comparative Evaluation

Compared to other moisture-retentive dressings such as hydrocolloids and foams, hydrogels offer distinct benefits, particularly their cooling effect and ability to conform to irregular wound shapes.[22] Hydrocolloids are better suited for wounds with moderate exudate, while foams are preferred for heavily exudating wounds due to their superior absorption capacity. However, hydrogels are often favored for their superior pain management, particularly in cases of burns and chronic wounds as shown in Table 1.[19]

Safety and Complications

Although hydrogels are thought to be safe in general, healthcare professionals should be aware of any potential problems. When using hydrogels, the main worry is the possibility of maceration, which occurs when the surrounding healthy tissue becomes too wet from extended contact with moisture.[10] Skin deterioration and an elevated risk of infection may result from this. It is crucial to continuously check the wound and modify the frequency of dressing changes following the exudate levels to reduce this danger. The risk of infection is an additional safety factor.[22] While hydrogels offer a moist environment that promotes healing, improper use of them can also foster an environment that is favorable to bacterial growth. Ensuring the wound is well cleaned and debrided is essential in rare cases, patients may experience allergic reactions to the materials used in hydrogels. While most hydrogels are made from biocompatible polymers, it is important to consider any known allergies or sensitivities when selecting a dressing. Hydrogels are a flexible and efficient treatment solution for a variety of wounds, including burns and chronic ulcers. Their calming qualities combined with the capacity to keep a moist wound environment make them especially useful in advancing healing and enhancing patient comfort. To guarantee results, it is crucial to evaluate the characteristics of the wound as well as any possible hazards related to the use of hydrogel.[21]

ABSORBABLE GELATIN SPONGES

Absorbable gelatin sponges have been a cornerstone in surgical hemostasis since their development in the early 1900s. They were originally designed to provide a reliable means of controlling bleeding, especially in situations where mechanical methods like sutures or cautery may be insufficient or impractical.[22,23] The key innovation of gelatin sponges lies in their ability to be absorbed by the body over time, reducing the need for subsequent surgeries to remove hemostatic materials.[24] Over the years, advancements in the composition and manufacturing of gelatin sponges have increased their effectiveness and adaptability in various surgical specialties. The sponges are typically derived from refined gelatin

Table 1: Detailed comparison of hydrogel dressings with other wound care products.[11-13;14-16]

Dressing Type	Moisture Retention	Absorption Capacity	Wound Type	Clinical Outcomes	Advantages
Hydrogel	High	Low to moderate	Pressure ulcers burn.	Accelerates healing, reduces pain.	Cooling effect, soothing.
Hydrocolloid	Moderate	Moderate to high	Surgical wounds, ulcers.	Promotes autolytic debridement and exudate management.	Longer wear time, forms gel.
Foam	Moderate	High	Heavily exuding wounds.	Reduces maceration risk and provides cushioning.	Highly absorbent and reduces dressing change.
Alginate	Low	Very high	Exudating wounds, cavity wounds.	Encourages clotting, highly absorbent.	Useful in bleeding wounds.

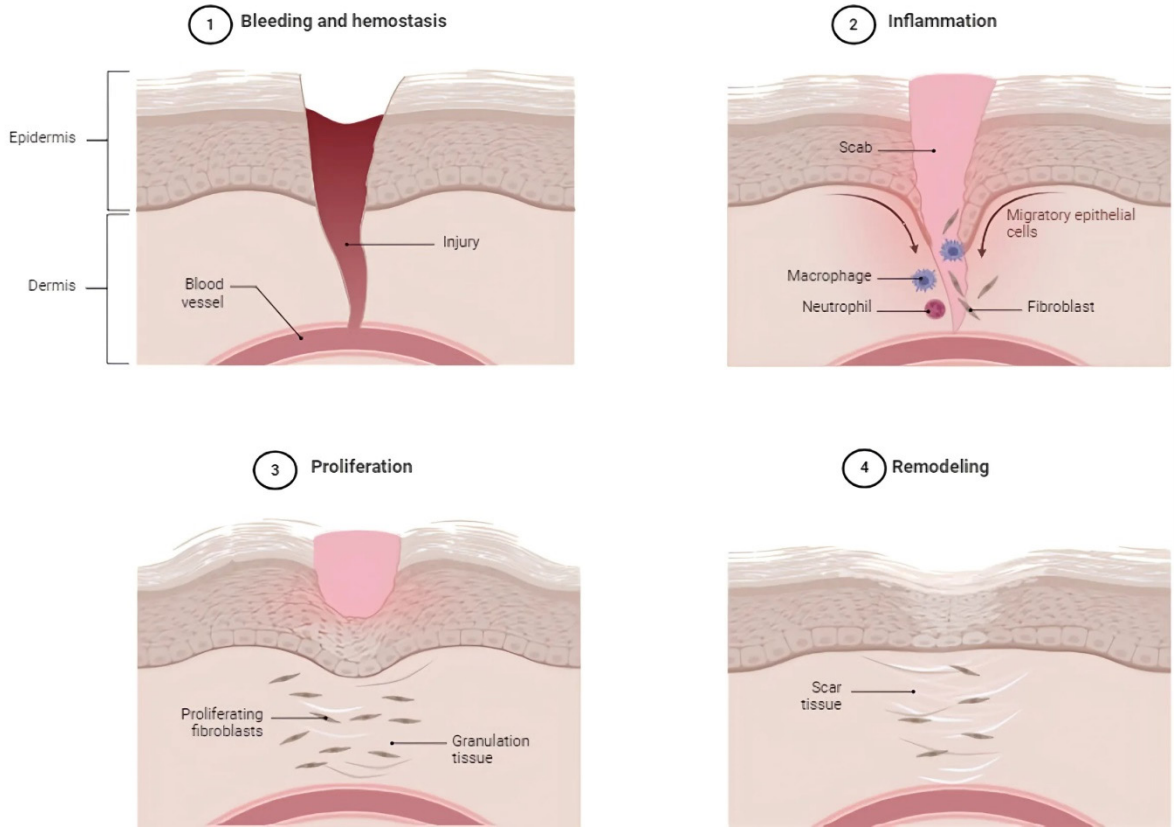

Figure 1: Stages of Wound Healing.[2-5]

sourced from pig skin, creating a porous, sponge-like structure that can absorb up to 40 times its weight in blood and other bodily fluids.[25,26] This high absorption capacity, coupled with their ability to conform to irregular surfaces, makes gelatin sponges especially valuable in surgeries involving delicate tissues or complex anatomy.[27-30]

Mechanism of Action

Absorbable gelatin sponges function primarily through mechanical means to control bleeding. When placed on a bleeding site, the sponge absorbs blood, expands and physically blocks blood flow as shown in Figure 2. This tamponade effect is further enhanced by the sponge's porous structure, which accelerates the body's natural clotting cascade by facilitating platelet activation and fibrin clot formation.[31] The sponge thus acts as a scaffold for clot formation, while also providing a surface for the infiltration of fibroblasts and other cells essential for wound healing.[33-35] A significant feature of gelatin sponges is their bioresorbability. Once hemostasis is achieved, the sponge gradually degrades and is absorbed by the body, typically within four to six weeks. This

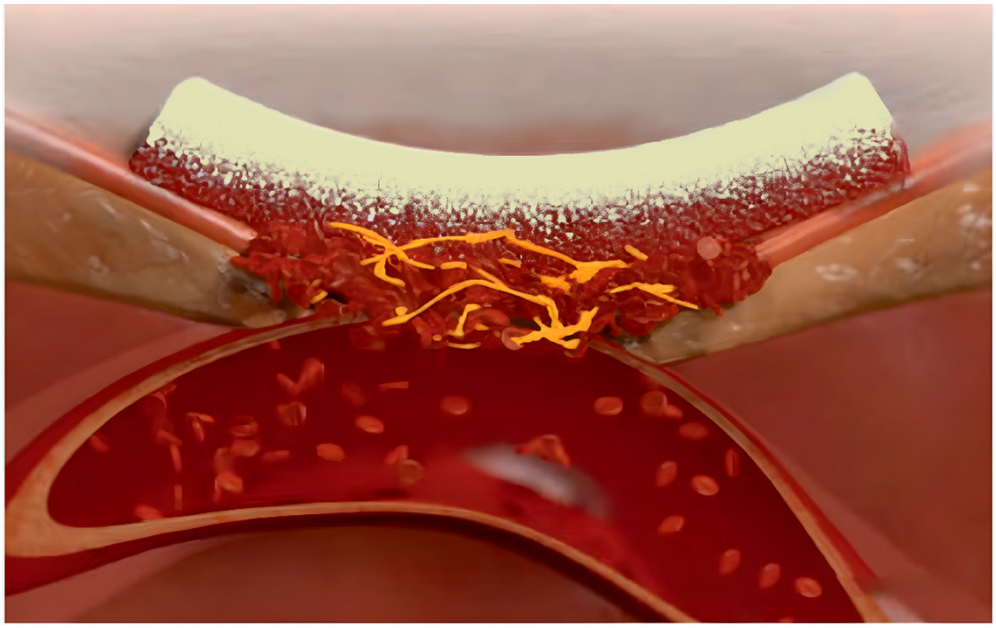

Figure 2: Absorbable Gelatin Sponge on a Bleeding Site.[31-35]

absorption eliminates the need for the sponge's removal, which is particularly advantageous in surgeries where it is undesirable to leave permanent materials in the body.[32]

Clinical Applications in Surgery

Gelatin sponges are highly versatile and have been used in a wide range of surgical procedures. In general surgery, they are commonly used to control bleeding from vascular organs such as the liver, spleen and kidneys. The sponges are particularly useful in managing diffuse oozing, where sutures or cauterization might not be feasible without causing further tissue damage.[34] In orthopedic surgery, gelatin sponges are often employed to control bleeding from bone surfaces, such as during hip or knee replacements, where they can be packed into bone defects or placed around hardware to minimize blood loss.[33] In neurosurgery, gelatin sponges are frequently used to control bleeding from the brain, spinal cord and surrounding tissues. Their ability to conform to the irregular surfaces of the central nervous system makes them indispensable in delicate procedures, particularly for managing venous bleeding.[29] Cardiovascular surgeons also rely on gelatin sponges to control bleeding at graft sites and anastomoses, helping to reduce intraoperative blood loss and the need for transfusions.[38] Similarly, in otolaryngology, gelatin sponges are used in nasal, sinus and throat surgeries to prevent postoperative bleeding and promote healing.[36-38]

Clinical Efficacy

Numerous studies have demonstrated the efficacy of absorbable gelatin sponges in achieving hemostasis across different surgical specialties. For instance, in liver surgery, gelatin sponges have been shown to control bleeding as effectively as other hemostatic agents, while also offering the advantage of being fully absorbable, thus reducing the risk of foreign body reactions.[32] In orthopedic surgery, gelatin sponges can significantly reduce intraoperative blood loss. A study reported a 30% reduction in blood loss during hip replacement surgeries when gelatin sponges were used in conjunction with other hemostatic measures.[33] Neurosurgeons have found gelatin sponges to be particularly useful for controlling venous bleeding, as the sponges conform to the irregular surfaces of the brain and spinal cord, providing a stable matrix for clot formation.[29] Overall, clinical evidence supports the use of absorbable gelatin sponges as a reliable and effective method for achieving hemostasis in a variety of surgical settings.

Safety Profile and Complications

While absorbable gelatin sponges are generally considered safe, there are potential risks associated with their use. One major concern is the risk of infection, as the presence of the sponge in a wound can create an environment conducive to bacterial growth if proper aseptic technique is not maintained.[36] To mitigate this risk, it is essential to ensure the wound is thoroughly debrided before sponge application. Another complication is the potential for foreign body reactions, including granuloma formation or fibrosis, particularly in patients with hypersensitivity or autoimmune disorders.[37] Though this risk is generally low, it is important to use the smallest amount of sponge necessary and to apply it only to the bleeding area to reduce the likelihood of adverse reactions. Additionally, residual gelatin sponge material can interfere with postoperative imaging studies, complicating the interpretation of MRI or CT scans, particularly in neurosurgery and orthopedic surgery.[38] In rare cases, incomplete absorption of the sponge can lead to complications such as calcification or fibrosis, which may require surgical intervention. Thus, careful

application and monitoring are necessary to ensure the best outcomes.

OXIDIZED REGENERATED CELLULOSE (ORC)

Oxidized Regenerated Cellulose (ORC) is a bioabsorbable hemostatic agent widely utilized in advanced wound care and surgical settings. ORC is derived from cellulose, the most abundant biopolymer in nature, through an oxidation process that enhances its hemostatic properties while maintaining bioabsorbability. Its versatility and biocompatibility make ORC essential for wound management, especially where infection risk is high or conventional methods are impractical. This review discusses the chemical properties, mechanisms of action, clinical applications and safety profile of ORC, based on current evidence in the field. Oxidized Regenerated Cellulose (ORC) is a bioabsorbable hemostatic agent derived from cellulose, the primary structural polymer found in plant cell walls. ORC is typically produced by oxidizing regenerated cellulose sourced from wood pulp or cotton. The oxidation process increases its acidity, thereby enhancing its hemostatic properties when applied to bleeding tissues.[39] The final product is a white, fabric-like material that can be easily manipulated to conform to wound surfaces. The acidic nature of ORC facilitates interaction with blood components, promoting platelet aggregation and clot formation. ORC is fully bioabsorbable, breaking down into carbon dioxide and water over time, leaving no harmful residue in the body.[37-39]

Mechanisms of Action in Hemostasis and Wound Healing

ORC's primary hemostatic function is achieved through its acidic nature, which accelerates the body's intrinsic clotting cascade.[40] When applied to a bleeding surface, ORC fibers promote platelet aggregation and enhance fibrinogen conversion to fibrin, leading to clot stabilization.[41] Additionally, the physical properties of ORC contribute to hemostasis by providing a scaffold that supports the developing clot and prevents further blood loss.[42,43] Moreover, ORC has demonstrated antimicrobial properties, particularly against gram-positive bacteria, due to its acidic environment. This reduces the risk of infection and fosters a cleaner wound bed, making it valuable in treating wounds with high infection risk, such as chronic ulcers and post-surgical sites.[44] ORC is also bioabsorbable and studies show that it degrades without eliciting a significant inflammatory response, making it suitable for patients with hypersensitivity or autoimmune conditions. Clinical trials suggest that ORC is well-tolerated, producing minimal scarring or foreign body reactions during wound healing.[42,44]

Applications Beyond Hemostasis

Beyond its role in hemostasis, ORC is utilized in managing infected or chronic wounds due to its antimicrobial properties. When combined with other wound care products, such as collagen or foam dressings, ORC enhances the overall performance by providing both hemostatic and structural support.[45] This combination is particularly effective in chronic, non-healing wounds where additional tissue regeneration support is necessary.[46] In surgical applications, ORC is valued for its conformability, especially in procedures where suturing or cauterization may be challenging or contraindicated. ORC can easily adhere to irregular or delicate surfaces, making it an essential tool in neurosurgery, orthopedic procedures and other complex surgeries where traditional hemostatic methods might be impractical.[47]

Clinical Evidence and Safety Profile

The efficacy of ORC in achieving rapid hemostasis is well-documented in clinical studies. One study demonstrated that ORC significantly reduced bleeding time compared to conventional hemostatic agents in patients undergoing cardiovascular surgery.[45] Furthermore, ORC's role in reducing postoperative infection rates has been emphasized, particularly in high-risk surgical sites.[48] ORC's safety profile is generally favorable, with a low incidence of adverse effects. Long-term follow-ups in clinical trials have shown that ORC is absorbed without inducing significant inflammatory or foreign body reactions, even in immunocompromised or hypersensitive patients.[49] However, appropriate use and careful placement are critical to ensuring optimal outcomes, as over-application or misapplication could delay healing or provoke localized tissue reactions. Oxidized regenerated cellulose is a versatile and effective agent in wound care and surgical settings. It offers hemostatic, antimicrobial and structural benefits, with a favorable safety profile. Its biocompatibility and minimal inflammatory response make it a preferred choice for managing a range of wounds, including those at high risk of infection. The broad applications of ORC, from chronic wound care to delicate surgeries, underscore its importance in modern healthcare. Further research into its combination with other wound care therapies could unlock even greater potential in tissue regeneration and wound healing.

COLLAGEN WOUND DRESSINGS

Collagen wound dressings are advanced wound care products designed to enhance the healing process of various types of wounds, particularly chronic and non-healing wounds. Collagen, a naturally occurring protein, is a vital component of the Extracellular Matrix (ECM), providing structural support and aiding tissue regeneration. By leveraging the body's inherent healing capabilities, collagen dressings promote new tissue formation, reduce inflammation and manage wound exudate. They are particularly beneficial for treating wounds where natural healing processes are impaired, such as in pressure ulcers, diabetic foot ulcers and venous leg ulcers. Collagen dressings come in various forms, including sheets, powders and gels, making them suitable for both chronic and acute wound care. Collagen dressing's support wound healing through several key

mechanisms. First, they provide a scaffold for the deposition of new cells, such as fibroblasts and keratinocytes, which are critical for wound closure and tissue regeneration, helping to replace damaged tissue and restore the integrity of the skin.[52] Collagen dressings also play a significant role in modulating the inflammatory phase of wound healing. Chronic wounds often remain in this phase due to an excess of pro-inflammatory cytokines and collagen dressings help to reduce the levels of these cytokines, promoting a more balanced healing response.[50,51] Additionally, collagen stimulates angiogenesis, the formation of new blood vessels, which is crucial for delivering nutrients and oxygen to the wound site, supporting tissue repair and regeneration.[53] Another vital function of collagen dressings is their ability to bind to and inactivate proteases, which are often elevated in chronic wounds and impede healing by degrading essential proteins and growth factors. By binding to these proteases, collagen dressings protect the wound bed and promote faster healing.[54] Finally, collagen dressings maintain a moist wound environment, which is conducive to cellular activity and tissue repair. A moist environment also aids in managing exudate and prevents tissue dehydration, a key factor in successful wound healing.

Clinical Efficacy

Collagen dressings have been widely studied for their effectiveness in wound healing. Numerous clinical trials and case studies have demonstrated their ability to accelerate healing, reduce wound size and improve overall patient outcomes, particularly in chronic wounds that have been resistant to standard treatments.[52] Collagen dressings have been shown to be especially effective in wounds with high levels of exudate and in wounds where the healing process has stalled.[52] For example, in a randomized controlled trial, patients with diabetic foot ulcers treated with collagen dressings exhibited significantly faster healing rates and reduced ulcer size compared to those receiving standard care alone. Another study focusing on pressure ulcers found that collagen dressings decreased healing times and minimized complications, making them a preferred option for patients with limited mobility.[54]

Safety Considerations

Collagen dressings are generally considered safe for most patients. However, caution should be exercised in individuals with known allergies to collagen derived from bovine or porcine sources. Additionally, while collagen dressings provide a moist environment that supports healing, they can also promote bacterial growth in infected wounds. Therefore, it is recommended that infected wounds be treated with antimicrobial therapy before applying collagen dressings. The choice of collagen dressing depends on the type and source of the collagen, as well as the specific needs of the wound. For example, bovine and porcine collagens are the most commonly used, but there are also synthetic alternatives for patients with allergies. The cost of collagen dressings is typically higher than that of standard dressings, but the potential for faster healing and better long-term outcomes often justifies the expense, especially in chronic or hard-to-heal wounds.[52,53]

Case Studies and Applications

Collagen dressings are particularly effective in managing complex wounds such as pressure ulcers, diabetic foot ulcers, venous leg ulcers and surgical wounds. In pressure ulcers, collagen dressings provide an optimal environment for healing by maintaining moisture, reducing exudate and preventing further tissue damage. In diabetic foot ulcers, they have been shown to significantly reduce healing times, reduce the risk of infection and improve patient comfort.[50] In surgical applications, collagen dressings not only support the healing of incisions but also help prevent hypertrophic scar formation, a common complication in surgical wound healing. These dressings are therefore valuable in postoperative care, particularly for patients at higher risk of poor wound healing, such as those with diabetes or limited mobility.[54] Collagen wound dressings represent a crucial advancement in wound care, particularly for chronic and non-healing wounds. Their ability to provide structural support, modulate inflammation, promote angiogenesis and manage protease activity makes them highly effective in a wide range of wound types. While cost and potential allergic reactions should be considered, the benefits of collagen dressings-faster healing, reduced complications and improved patient outcomes make them a valuable option in both acute and chronic wound management.

STERILIZED BONE WAX

Sterilized bone wax has been a critical tool for managing bleeding from bone surfaces in surgery for over a century. Its primary role is in orthopedic, neurosurgical and maxillofacial procedures where traditional hemostatic techniques may not be as effective. Historically, bone wax was introduced in 1892 by Sir Victor Horsley, a neurosurgeon, who needed a solution to control bleeding from cancellous bone.[56-58] Despite advancements in surgical hemostatic technologies, such as absorbable gelatin sponges and oxidized regenerated cellulose, bone wax remains widely used due to its simplicity, stability and immediate effectiveness. The continued use of bone wax is grounded in its unique properties, including its capacity to physically obstruct blood flow from the bone, ease of manipulation during surgery and its minimal biological reactivity.[55] This historical resilience suggests that, despite limitations, bone wax provides unmatched utility in specific clinical scenarios.

Composition and Properties

Sterilized bone wax is primarily composed of beeswax, which has been used in various medical applications for centuries due to its

Table 2: Comparative Efficacy of Advanced Wound Care Products.[14-28,35-38,40-45,50-53,55-58,60-62]

Product Type	Moisture Retention	Absorption Capacity	Wound Types	Clinical Outcomes	Advantages	Complications
Hydrogels	High	Low to Moderate	Burns, pressure ulcers, diabetic foot ulcers, superficial wounds.	Accelerates epithelial migration, promotes autolytic debridement, reduces pain and cooling effect.	Creates a moist environment, reduces pain, easy to monitor.	Risk of maceration if overused, limited absorption for high-exudate wounds.
Hydrocolloids	Moderate to High	Moderate	Surgical wounds, ulcers (venous, pressure).	Promotes autolytic debridement, exudate management and long wear time.	Forms a gel-like barrier, occlusive, suitable for moderate exudate.	Can lead to skin maceration or odor, may cause allergic reactions in sensitive patients.
Foam Dressings	Moderate	High	Heavily exudating wounds, cavity wounds.	Reduces risk of maceration, cushions wound provides moisture balance.	Absorbs large amounts of exudate and reduces dressing frequency.	Can dry out the wound if left on too long, not suitable for dry wounds.
Alginate Dressings	Low	Very High	Heavily exuding wounds, bleeding wounds, cavity wounds.	Encourages clotting, reduces exudate and promotes granulation tissue formation.	Highly absorbent, useful in bleeding wounds and maintains a moist wound bed.	Can cause excessive drying of the wound and requires a secondary dressing.
Collagen Dressings	High	Moderate	Chronic wounds, diabetic foot ulcers and venous leg ulcers.	Promotes new tissue growth, enhances angiogenesis and manages protease activity.	Supports cellular activity, modulates inflammation and reduces wound size.	Allergic reactions (especially if bovine or porcine derived), risk of infection if used on infected wounds.
Absorbable Gelatin Sponges	Low to Moderate	High	Surgical wounds, bleeding from bone surfaces.	Achieves rapid hemostasis, reduces the need for transfusions and supports clot formation.	Easily conforms to irregular surfaces, absorbed by the body over time.	Risk of infection or granuloma formation if not fully absorbed.
Oxidized Regenerated Cellulose (ORC).	High	Low	Chronic wounds, infected wounds, surgical application.	Accelerates hemostasis, reduces infection risk, bioabsorbable.	Provides both hemostatic and antimicrobial benefits, easily conformable.	Can interfere with imaging (MRI/CT), potential for localized tissue reactions if over-applied.
Silicone Gel Sheets	Low	Minimal	Hypertrophic scars, keloids, post-surgical scars.	Reduces scar thickness and redness and improves scar flexibility.	Non-invasive, easy to apply and suitable for continuous wear.	Requires long-term use (12-24 hr a day), risk of irritation, costly for large scars.

pliability and hydrophobic nature.[55] To improve its workability in surgical settings, beeswax is often softened with agents such as paraffin, isopropyl palmitate, or petroleum jelly, which enhance its ability to mold into irregular bone surfaces. This combination of components ensures that bone wax remains stable and adheres effectively to the bone without being absorbed or dissolved in the surrounding blood or tissue fluids. Although beneficial in creating a solid seal over bleeding bone, its hydrophobicity also presents a challenge. Studies have demonstrated that bone wax, being non-resorbable, can impede the healing process by physically blocking bone regeneration.[58] Additionally, the product's inert nature means it does not actively participate in the body's natural hemostatic or immune responses, relying entirely on its mechanical properties for effectiveness.[56] Several researchers have explored attempts to modify bone wax to improve its bioactivity, with studies focusing on adding resorbable components or bioactive molecules that could promote bone healing while retaining hemostatic efficacy.[57]

Mechanism of Action

The mechanism of bone wax differs substantially from other hemostatic agents. While products like absorbable gelatin sponges and oxidized regenerated cellulose encourage the body's natural clotting mechanisms, bone wax functions purely as a mechanical barrier. Once applied to a bleeding bone surface, it adheres and physically seals off the bleeding vessels, preventing further blood loss.[58] This process does not involve any biological interaction with the coagulation cascade, making it effective in situations where the bone itself is the primary source of bleeding rather than vascular structures. This mechanical action, while effective in halting bone bleeding, has limitations. Since bone wax does not promote clot formation or tissue regeneration, its use in areas where bone growth is critical can hinder post-surgical recovery. For example, research has shown that applying bone wax in spinal surgery can inhibit osteogenesis, leading to delayed or incomplete healing.[56] Therefore, surgeons must balance the need for immediate hemostasis with the potential long-term effects on bone repair.

Applications in Surgery

Sterilized bone wax has been significant in several surgical disciplines and its applications extend far beyond orthopedic procedures. In neurosurgery, bone wax is invaluable for controlling bleeding from the skull during craniotomies, where it is applied along the cut bone edges to maintain a clear field and prevent blood from obscuring the surgical view.[55] In orthopedic surgery, particularly during joint replacements or osteotomies, bone wax is used to manage bleeding from cancellous bone, which tends to ooze due to its spongy structure.[58] In procedures such as hip and knee replacements, where large volumes of bone are often exposed and cut, bone wax helps to minimize blood loss, reducing the need for transfusions and facilitating smoother procedures. In cardiothoracic surgery, bone wax is commonly applied to the sternum following sternotomy. A study by Jackson *et al*. found that bone wax significantly reduces intraoperative blood loss during sternotomies, although concerns regarding its interference with bone healing in this context persist.[57] Despite these benefits, surgeons must exercise caution, particularly in procedures that require bone healing. Studies have shown that the non-resorbable nature of bone wax can lead to foreign body reactions, including granuloma formation and infection, especially in contaminated surgical fields.[56] The risk of infection is compounded in cases where residual bone wax is left in place postoperatively, which may serve as a nidus for bacterial colonization.[58]

Safety and Complications

While sterilized bone wax is a highly effective hemostatic agent, its safety profile is not without complications. The most significant risks associated with bone wax include foreign body reactions and impaired bone healing. In rare cases, the body may mount an inflammatory response to the wax, resulting in the formation of granulomas, which can complicate the healing process.[55] Additionally, because bone wax is biologically inert and non-resorbable, it can persist at the surgical site long after the operation, leading to chronic inflammation or infection. A study by Hirsch and Dubberke highlighted the risk of impaired osteogenesis associated with bone wax.[56] Their research showed that in procedures such as spinal fusions, where bone regeneration is critical, the use of bone wax can inhibit the formation of new bone tissue, delaying healing and increasing the risk of non-union. This risk necessitates careful consideration, particularly in patients undergoing procedures that require robust bone healing. The risk of infection is another complication to consider. Although bone wax does not directly support bacterial growth, its presence in the wound can create an environment conducive to infection. Surgeons must balance the need for hemostasis with the potential long-term complications associated with leaving a non-resorbable foreign material in the body.[58] However; Sterilized bone wax remains a critical tool in surgical practice, particularly in procedures involving bones. Its simplicity and mechanical action provide a reliable method for achieving hemostasis in situations where other agents may not be effective. However, its non-resorbable nature and potential to interfere with bone healing limit its application in surgeries where bone regeneration is essential. Ongoing research into modified forms of bone wax that incorporate bioresorbable components or pro-healing factors may offer solutions to these limitations, but until then, careful surgical application and patient selection are critical to minimizing complications and ensuring optimal outcomes.

SILICONE GEL SHEET

Silicone gel sheets have emerged as a leading non-invasive treatment for managing hypertrophic and keloid scars. Since their introduction in the 1980s, they have become a gold standard in scar management, with numerous studies attesting to their efficacy in flattening, softening and improving the cosmetic appearance of scars. Silicone gel sheets offer a flexible, easy-to-use treatment option for scars that can be worn continuously and applied to a variety of scar types, making them highly versatile.[59] These sheets come in different sizes and shapes, tailored to specific scar locations, such as joints or large surface areas. The exact mechanisms by which silicone gel sheets improve scar outcomes are not fully understood, but several hypotheses have been proposed based on both clinical experience and scientific studies. A leading theory is that the sheets work by increasing hydration in the uppermost layer of the skin (stratum corneum). This occlusive barrier effect prevents water loss, maintaining a moist environment that is thought to inhibit excessive collagen deposition-a key factor in the formation of hypertrophic and keloid scars.[59] Additionally, silicone sheets are believed to regulate the temperature and pressure around the scar site, which may influence fibroblast activity and collagen remodeling.[61] By applying gentle pressure to the scarred area, the sheets help to flatten raised scars over time. The sheets may also reduce capillary activity, which limits blood flow and decreases the production of inflammatory cytokines, reducing the risk of excessive scar tissue formation. Some evidence suggests that silicone influences the levels of Transforming Growth Factor-beta (TGF-β), a cytokine implicated in the development of hypertrophic and keloid scars, although more research is needed to fully confirm these biochemical effects.

Clinical Applications

Silicone gel sheets are widely utilized across various medical specialties, particularly in post-surgical, trauma and burn care. Post-surgical scars are one of the most common indications, where silicone gel sheets are applied to clean, healed incisions to prevent the formation of hypertrophic scars. Studies have demonstrated a significant reduction in scar thickness and redness when silicone sheets are used early in the healing process.[62] In burn scar management, silicone gel sheets are often used to reduce scar elevation and improve flexibility in scarred skin. Burn scars, which are prone to thickening and contracting, benefit from the continuous hydration and mechanical pressure provided by silicone sheets, which help to prevent contractures and improve the skin's appearance and function.[60] Cosmetic procedures, such as breast augmentation or abdominoplasty, also utilize silicone sheets to minimize visible scarring. In these cases, patients apply silicone sheets shortly after suture removal to reduce the risk of unsightly scarring.

Efficacy and Safety Considerations

Numerous clinical studies support the effectiveness of silicone gel sheets in improving scar outcomes. A systematic review by O'Brien and colleagues (2009) found that silicone gel sheets significantly reduced scar thickness, erythema and pliability, particularly when applied within the first few weeks after wound closure. The sheets are generally considered safe for long-term use, as they are hypoallergenic and can be applied continuously for months without significant adverse effects. However, successful outcomes depend heavily on patient compliance, as silicone sheets must be worn for 12-24 hr a day over several months to achieve the desired results.[60] Some patients may experience skin irritation or maceration, particularly if the sheets are not cleaned regularly or are applied to sensitive skin. For larger scars, the cost of long-term treatment with silicone sheets can also become prohibitive, as patients may require multiple sheets over time. Despite these potential drawbacks, silicone gel sheets remain one of the most accessible, non-invasive treatments for scar management, with minimal risk of serious complications compared to other treatments, such as corticosteroid injections or laser therapy.[63]

Comparative Analysis with Other Products

Silicone gel sheets are often compared to other scar treatment modalities, including silicone gel ointments, pressure garments, corticosteroid injections and laser therapy. While silicone gels (topical ointments) provide the same occlusive benefits, they lack the mechanical pressure that sheets offer, which may be critical for flattening raised scars.[59] Pressure garments, commonly used for large burn scars, offer continuous pressure but can be cumbersome and difficult to wear for long periods, especially in hot climates or for active individuals. Corticosteroid injections, a common treatment for hypertrophic and keloid scars, help reduce inflammation and collagen production, but they carry risks of side effects like skin atrophy, pigmentation changes and pain at the injection site. Laser therapy can improve scar appearance by resurfacing the skin and reducing pigmentation or thickness, but it is more invasive, costly and may require multiple sessions to achieve optimal results.[63] In comparison, silicone gel sheets are non-invasive, cost-effective for small-to-medium scars and easy to apply, making them a preferred option for many patients and clinicians. However, Silicone gel sheets are a widely endorsed and effective treatment for hypertrophic and keloid scars, offering both occlusive and pressure-based benefits. While their exact mechanism of action is not fully understood, their ability to improve hydration, reduce cytokine production and regulate collagen deposition has been well-documented. Though consistent use is required for maximum efficacy, their safety profile, ease of use and cost-effectiveness in many cases make them a popular choice for scar management. Comparative studies in Table 2 suggest that while other treatments like corticosteroid

injections and laser therapy are effective, silicone gel sheets provide a safer, non-invasive alternative with fewer side effects.

SAFETY CONSIDERATIONS IN ADVANCED WOUND CARE PRODUCTS

Advanced wound care products, such as collagen dressings, bone wax and silicone gel sheets are essential tools in clinical practice. However, their use involves several safety concerns that must be carefully addressed to ensure optimal healing outcomes and avoid complications. These concerns include patient-specific factors, infection control and material biocompatibility. When selecting wound care products, it is crucial to consider the individual patient's medical background. Allergies to certain materials, though rare, can pose risks. For example, collagen dressings derived from bovine or porcine sources may trigger allergic reactions in some patients. Identifying these sensitivities through a detailed patient history is essential to prevent delayed healing and potential complications. Chronic conditions, such as diabetes or peripheral artery disease, can also affect wound healing. Diabetic patients, for instance, often suffer from impaired vascularization and nerve function, which slows down the healing process and increases infection risk. Wound care strategies in such cases should focus on products that balance hemostasis with moisture management and infection prevention, such as absorbable options like collagen or Oxidized Regenerated Cellulose (ORC) dressings.

Immunocompromised patients, including those undergoing chemotherapy or with conditions like HIV, face additional risks. Their weakened immune systems make them more susceptible to infections, necessitating the use of antimicrobial dressings like ORC, which can reduce bacterial load in wounds. Nevertheless, in these patients, close monitoring is essential because delayed inflammatory responses may obscure early signs of complications.

Infection control is another critical factor in wound care management. Ensuring the sterility of wound care products, especially in surgical settings, is vital to preventing infection. Sterilized bone wax and collagen dressings must be handled with care to maintain their sterility during application. Improper handling can introduce pathogens, leading to severe complications like osteomyelitis in bone surgeries. Research has shown that sterile collagen dressings significantly lower infection rates in clean-contaminated surgical sites compared to non-sterile alternatives.

Many advanced wound care products incorporate antimicrobial properties to reduce the risk of infection. For instance, ORC creates an acidic environment that inhibits bacterial growth while promoting hemostasis. This dual functionality is particularly beneficial for wounds at high risk of infection. However, excessive use of antimicrobial agents must be balanced against the risk of developing antimicrobial resistance, a growing concern in healthcare. Regular wound assessment and debridement, along with judicious use of antimicrobial dressings, are crucial components of infection management. Patients and caregivers should be educated to recognize early signs of infection, such as increased redness, swelling, or exudate, to ensure timely interventions.

Material biocompatibility is a key consideration in the selection of wound care products. Biodegradable materials, like collagen dressings and ORC, are preferred for their ability to be absorbed by the body over time, minimizing the risk of foreign body reactions or chronic inflammation. Non-biodegradable products, such as bone wax, can remain in the body indefinitely. This can lead to complications like fibrosis or infection if not carefully managed. Studies have noted that bone wax, while effective for hemostasis, is associated with a small but significant risk of foreign body reaction, especially in surgeries where bone regeneration is critical.

Toxicity is another aspect to be addressed in the development of advanced wound care products. These products should be free from harmful chemicals or residues that could impede the healing process. For example, silicone gel sheets, which are widely used in scar management, are generally considered safe. However, some studies have reported mild skin irritation in sensitive patients after prolonged use. To minimize these risks, rigorous quality control and regulatory oversight during manufacturing are essential, ensuring that products are safe for extended use on healing tissues.

In summary, the use of advanced wound care products involves several important safety considerations. Patient-specific factors, such as allergies, chronic conditions and immune status, must guide the choice of products to prevent adverse reactions and ensure optimal healing. Infection control through sterility and the appropriate use of antimicrobial agents plays a critical role in minimizing complications. Finally, the biocompatibility and biodegradability of materials, along with the absence of toxic substances, are essential to ensure that these products support the healing process without causing harm. By addressing these safety concerns, clinicians can maximize the effectiveness of advanced wound care interventions and improve patient outcomes.

FUTURE DIRECTIONS AND INNOVATIONS IN ADVANCED WOUND CARE

The field of advanced wound care is experiencing rapid advancements, driven by emerging technologies that promise to improve patient outcomes and broaden treatment possibilities. Several key areas of innovation hold the potential for revolutionizing wound management.

Nanotechnology is one such area being actively explored. Nanomaterials, such as nanofibers, nanoparticles and nanoscale hydrogels, are being engineered to deliver drugs, growth factors

and antimicrobial agents directly to the wound site. These nanoscale systems not only promote faster wound healing but also help in reducing infection risks by targeting harmful bacteria with precision. For instance, silver nanoparticles have shown promise in accelerating healing and reducing bacterial colonization, particularly in chronic wounds. These developments highlight the growing interest in harnessing nanotechnology to offer more sophisticated wound-healing solutions.

3D printing technology is another innovative tool with transformative potential in wound care. It is being used to create customized wound care products like scaffolds and dressings that conform precisely to the dimensions and unique needs of a patient's wound. This personalized approach can lead to more effective treatment, reducing waste and ensuring better patient outcomes. Moreover, researchers are exploring the possibility of using biocompatible materials in 3D-printed wound dressings that could further enhance healing by providing structural support for cell growth and tissue regeneration. Advances in biomaterials are pushing the boundaries of wound care by developing products that closely mimic the body's natural healing processes. Synthetic collagen analogs, bioactive dressings and smart materials that respond to changes in the wound environment are under development. These smart dressings can adapt to the wound's moisture levels, oxygenation and temperature, ensuring an optimized healing environment. Bioactive dressings, which release therapeutic agents like growth factors and antimicrobial compounds, represent a significant leap forward in supporting the healing of chronic or non-healing wounds.

Gene therapy and regenerative medicine offer another exciting frontier in wound care. Gene therapy, for instance, could introduce genes that promote angiogenesis and tissue regeneration, offering hope to patients with chronic wounds or genetic disorders that impair healing. This approach is still in its early stages but shows promise for targeting underlying causes of impaired wound healing at the molecular level. Meanwhile, stem cell therapy is emerging as a potent tool for wound regeneration. Stem cells can promote the repair of damaged tissues and accelerate healing. Researchers are working to develop therapies that involve stem cells being applied directly to the wound site or used to create bioengineered skin grafts for large or difficult-to-heal wounds. Personalized medicine, which tailors treatments based on a patient's unique characteristics, is poised to have a significant impact on wound care. Genomic analysis can help identify patients who are at greater risk for complications such as poor wound healing or keloid formation, allowing clinicians to develop personalized treatment plans that target these risks. Tailoring wound care regimens to fit each patient's skin type, wound type and overall health can lead to better results and faster recovery times. For example, personalized care might involve the selection of specific dressings or therapeutic interventions based on a patient's genetic predisposition to certain complications.

Sustainability is also becoming a major focus, with researchers and manufacturers seeking to develop more eco-friendly wound care products. Biodegradable dressings made from natural materials are being developed to reduce environmental impact. Such products would break down naturally after use, preventing the buildup of medical waste. In addition, manufacturers are looking into sustainable sourcing of raw materials, energy-efficient production processes and recyclable packaging to make wound care products more eco-friendly. However, despite these promising advancements, the field faces several challenges. The high cost of many advanced wound care products and emerging technologies may limit access for patients in low-resource settings, making affordability a significant barrier. Additionally, regulatory hurdles for new technologies can delay their availability, as rigorous testing and approvals are required to ensure safety and efficacy. Patient compliance is another critical challenge, as the success of wound care depends heavily on patients following prescribed treatment regimens. Innovations that improve ease of use, comfort and convenience could help to improve adherence to care plans. Finally, continued investment in research and development is essential to drive innovation and address unmet needs in wound care.

CONCLUSION

In conclusion, the future of advanced wound care holds great promise, with innovations in biomaterials, drug delivery systems, monitoring technologies, regenerative medicine and sustainable practices paving the way for improved patient outcomes. These advancements will lead to more effective, safer and personalized wound care solutions, enhancing the quality of care for individuals with chronic and complex wounds. Ongoing research and development will continue to push the boundaries of what is possible, offering hope for better management of wounds in both clinical and home care settings.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

ABBREVIATIONS

ORC: Oxidized Regenerated Cellulose; **ECM:** Extracellular Matrix; **TGF-β:** Transforming Growth Factor-beta.

AUTHOR CONTRIBUTIONS

The sole author of this work, Anushree P. Munchinamane, was responsible for the research's conception, design, data acquisition, analysis and interpretation. The manuscript was written, edited and approved by the author.

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