WJPMR, 2026, 12(7), 43-53

Review Article

Impact Factor: 7.555

WORLD JOURNAL OF PHARMACEUTICAL AND MEDICAL RESEARCH

www.wjpmr.com

ISSN (O): 2455-3301
ISSN (P): 3051-2557
Coden USA: WJPMBB

VRANA ROPANA: AN AYURVEDIC AND MODERN REVIEW OF WOUND HEALING MECHANISMS, THERAPEUTIC INTERVENTIONS, AND EMERGING TRENDS

[1]*Dr. Malika Sharma, [2]Dr. Bhoomi Soni

[1]P.G. Schlolar, Department of Shalya Tantra, Quadra Institute of Ayurveda.
[2]Associate Professor, Department of Shalya Tantra, Quadra Institute of Ayurveda.

***Corresponding Author: Dr. Malika Sharma**
P.G. Schlolar, Department of Shalya Tantra, Quadra Institute of Ayurveda.

DOI: https://doi.org/10.5281/zenodo.20962354

How to cite this Article: [1]*Dr. Malika Sharma, [2]Dr. Bhoomi Soni. (2026). Vrana Ropana: An Ayurvedic and Modern Review Of Wound Healing Mechanisms, Therapeutic Interventions, And Emerging Trends. World Journal of Pharmaceutical and Medical Research, 12(7), 43-53.

This work is licensed under Creative Commons Attribution 4.0 International license.

Article Received on 18/05/2026 **Article Revised on 08/06/2026** **Article Published on 01/07/2026**

ABSTRACT

Wound healing is a highly coordinated biological process that plays a vital role in restoring tissue structure and function after injury. This review presents an extensive discussion on the mechanisms, influencing factors, and therapeutic approaches associated with wound healing, particularly emphasizing chronic wounds and vulnerable patient groups. The major stages of wound healing—hemostasis, inflammation, proliferation, and remodeling—are explained along with the cellular and molecular activities regulated by platelets, immune cells, cytokines, and growth factors. Different factors affecting wound repair, including patient- related, local, and systemic conditions, are analyzed for their effects on healing efficiency. Various treatment strategies such as wound dressings, surgical interventions, and advanced therapies including stem cell and growth factor therapy are also reviewed. The management of chronic wounds is discussed with attention to the complexities involved and the importance of multidisciplinary care. Special populations, such as children, elderly individuals, and patients with conditions like diabetes and autoimmune disorders, are highlighted because of their distinctive healing responses and clinical requirements. Furthermore, the significance of biomaterials and tissue engineering in enhancing tissue repair and regeneration is explored, focusing on scaffolds, matrices, and bioactive substances. Future perspectives in wound healing research are also presented, including technological innovations, emerging therapeutic possibilities, and current challenges in improving wound care outcomes. This review offers valuable knowledge for healthcare professionals and researchers by underlining the importance of understanding wound healing mechanisms to improve patient management and recovery.

KEYWORDS: Wound healing, chronic wounds, special populations, biomaterials, tissue engineering, growth factors, stem cell therapy.

INTRODUCTION

Wound healing is a complex and carefully regulated physiological process that is essential for tissue repair and the restoration of skin integrity. This process involves a sequence of interconnected cellular and molecular events that work together to achieve effective healing. The major phases of wound healing—hemostasis, inflammation, proliferation, and remodeling—are controlled by numerous growth factors, cytokines, and different cell types including platelets, neutrophils, macrophages, fibroblasts, and keratinocytes.

Under normal conditions, wound healing progresses systematically through these stages, ultimately restoring the structure and function of damaged tissue. However, in some situations such as chronic wounds, the healing process becomes disrupted, resulting in delayed or incomplete recovery. Chronic wounds are characterized by persistent inflammation and an inability to advance through the normal phases of healing, creating a major clinical problem associated with high morbidity and increased healthcare expenses.

Apart from its clinical significance, wound healing is also an important aspect of everyday life. Minor injuries such as cuts, abrasions, and scrapes are common experiences for most individuals. Knowledge of the fundamental principles of wound healing can help people manage minor injuries effectively and encourage faster recovery. Appropriate wound care practices, including cleaning the injured area, using suitable dressings, and observing for signs of infection, can reduce complications and support proper healing.

A thorough understanding of the pathological processes responsible for impaired wound healing is necessary for the development of targeted treatment approaches. Therefore, this review aims to provide a detailed overview of the cellular and molecular mechanisms involved in both normal and abnormal wound healing. By improving our understanding of wound healing pathophysiology, this review seeks to support the development of innovative therapeutic strategies for the effective treatment of chronic wounds.

PHASES OF WOUND HEALING

Wound healing is a multifaceted and continuously evolving process that depends on the coordinated interaction of various cellular and molecular mechanisms. It is generally classified into four overlapping stages: hemostasis, inflammatory phase, proliferative phase, and remodeling phase.

Remodeling Phase

The remodeling phase, also referred to as the maturation stage, represents the final phase of wound healing and may continue for several months or even years. During this stage, the newly developed tissue is reorganized through the rearrangement and cross-linking of collagen fibers, which enhances the tensile strength of the scar tissue. Simultaneously, wound contraction occurs, decreasing the wound size and improving the overall appearance of the healed area. This phase is crucial for restoring the structural stability and functional integrity of the affected tissue.

The stages of wound healing are closely interconnected and overlap with one another, where the successful completion of one phase is necessary for the progression of the next. Any disturbance or imbalance within these stages can result in delayed healing or chronic wound formation. Therefore, understanding the different phases of wound healing is essential for healthcare professionals involved in wound management and patient care.

CELLULAR AND MOLECULAR MECHANISMS

1. *Role of Platelets*

Platelets have a significant function in the early stages of wound healing, mainly through their contribution to hemostasis and the secretion of growth factors and cytokines.

1) *Hemostasis*

Immediately after tissue injury, blood vessels constrict to minimize blood loss. Platelets adhere to the exposed collagen at the damaged site and aggregate to form a temporary clot that helps stop bleeding. During this process, platelets release von Willebrand factor (vWF), which enhances platelet adhesion, and serotonin, which promotes vasoconstriction and further limits blood flow.

2) *Release of Growth Factors and Cytokines*

Activated platelets contain α-granules rich in growth factors and cytokines that are released at the wound site. Platelet-derived growth factor (PDGF) promotes the migration and multiplication of fibroblasts, smooth muscle cells, and endothelial cells, thereby supporting granulation tissue formation and angiogenesis. Transforming growth factor-beta (TGF-β) regulates cellular growth, differentiation, and extracellular matrix synthesis, all of which are important for tissue repair and remodeling.

In addition, platelets release inflammatory mediators such as interleukin-1 (IL-1) and tumor necrosis factor-alpha (TNF-α), which attract immune cells to the injured area and initiate the inflammatory response necessary for healing.

3) *Regulation of the Inflammatory Response*

Platelets also interact with leukocytes and endothelial cells, thereby influencing inflammation. They increase leukocyte adhesion to the vascular endothelium and facilitate the migration of immune cells into the injured tissue, supporting the inflammatory phase of wound healing.

4) *Angiogenesis*

Platelets secrete angiogenic substances including vascular endothelial growth factor (VEGF) and basic fibroblast growth factor (bFGF). These factors stimulate the development of new blood vessels within the wound bed, ensuring an adequate supply of oxygen and nutrients required for tissue regeneration and repair.

2. *White Blood Cells and Other Immune Cells*

White blood cells (WBCs) and other immune cells are essential components of wound healing because they coordinate the inflammatory response, remove debris, and support tissue regeneration. Their roles are described below:

1) *Neutrophils*

Neutrophils are the earliest immune cells to reach the wound site, typically arriving within a few hours after injury. Their primary function is to engulf and destroy bacteria, cellular debris, and dead cells through phagocytosis, thereby cleaning the wound and preventing infection. Neutrophils also release cytokines and chemokines that attract additional immune cells to the wound area and intensify the inflammatory response.

2) *Macrophages*

Macrophages are key regulators of both the inflammatory and tissue repair phases of wound healing. During the early inflammatory stage, they strengthen the inflammatory response by secreting pro-inflammatory cytokines and growth factors. In later stages, macrophages contribute to tissue repair by promoting fibroblast activity, collagen synthesis, angiogenesis, and extracellular matrix formation, all of which are necessary for effective wound healing.

Pro-inflammatory cytokines such as interleukin-1 (IL-1), interleukin-6 (IL-6), and tumor necrosis factor-alpha (TNF-α). As healing progresses into the repair stage, macrophages shift toward a tissue-repairing or pro-healing phenotype that supports regeneration and remodeling of damaged tissue. These reparative macrophages release growth factors including transforming growth factor-beta (TGF-β) and platelet-derived growth factor (PDGF), which encourage fibroblast multiplication and collagen production.

3) *Lymphocytes*
Lymphocytes, including T lymphocytes and B lymphocytes, contribute mainly to the regulation of the wound healing process. T cells regulate immune activity through the secretion of cytokines that may either enhance or inhibit inflammation depending on the stage of healing. B cells assist in host defense by producing antibodies that help eliminate microorganisms from the wound area.

4) *Mast Cells*
Mast cells are particularly active during the initial inflammatory stage of wound healing. They release histamine and other inflammatory substances that cause vasodilation and increase vascular permeability. This process enables immune cells to migrate more efficiently to the injured tissue and supports the inflammatory response required for healing.

5) *Other Immune Cells*
Additional immune cells, such as dendritic cells and natural killer (NK) cells, also participate in wound repair, although their exact roles are not completely understood. Dendritic cells may contribute to the coordination of immune responses and tissue regeneration, while natural killer cells help remove infected or damaged cells from the wound site.

3. *Cytokines and Growth Factors*
Cytokines and growth factors are essential mediators in wound healing because they regulate inflammation, cellular proliferation, migration, and extracellular matrix (ECM) formation. Their important functions are discussed below:

1) *Cytokines*
a) Interleukin-1 (IL-1)
IL-1 is a major pro-inflammatory cytokine that has a significant role during the early stages of wound healing. It enhances inflammation, attracts immune cells to the wound region, and stimulates the release of additional cytokines and growth factors.

b) *Interleukin-6 (IL-6)*
IL-6 is another important inflammatory cytokine involved in regulating immune reactions and stimulating acute-phase protein synthesis. It also supports the proliferation and differentiation of several cell types participating in tissue repair.

c) *Tumor Necrosis Factor-alpha (TNF-α)*
TNF-α is a strong pro-inflammatory cytokine mainly secreted by macrophages. It promotes inflammatory activity, recruits immune cells to the injured tissue, and stimulates the production of other cytokines and growth factors involved in healing.

d) *Interleukin-8 (IL-8)*
IL-8 functions as a chemokine that is essential for attracting neutrophils to the wound area. It contributes to the early inflammatory response and assists in the removal of pathogens and cellular debris from the wound.

2) *Growth Factors*
a) Platelet-Derived Growth Factor (PDGF)
PDGF is produced by platelets and macrophages and plays an important role in tissue repair. It stimulates the proliferation and migration of fibroblasts, endothelial cells, and smooth muscle cells, thereby supporting granulation tissue formation and angiogenesis.

b) *Transforming Growth Factor-beta (TGF-β)*
TGF-β is a multifunctional growth factor that controls several aspects of wound healing, including inflammation, cell growth, differentiation, and extracellular matrix production. It contributes to granulation tissue development and regulates fibroblast and immune cell activity.

c) *Vascular Endothelial Growth Factor (VEGF)*
VEGF is a major regulator of angiogenesis and promotes the development of new blood vessels within the wound bed. These blood vessels provide oxygen and nutrients necessary for tissue repair and regeneration.

d) *Fibroblast Growth Factor (FGF)*
FGFs stimulate the growth and migration of fibroblasts, endothelial cells, and keratinocytes. They play a key role in extracellular matrix synthesis, angiogenesis, and re-epithelialization during the healing process.

ANGIOGENESIS AND FIBROPLASIA

Angiogenesis
Angiogenesis refers to the formation of new blood vessels from existing vascular structures and is a fundamental process in wound healing. This process is regulated through a coordinated interaction of endothelial cells, growth factors, and extracellular matrix components. Angiogenesis is essential because it ensures an adequate supply of oxygen and nutrients to the wound area, assists in the removal of metabolic waste

products, and supports the migration of inflammatory and reparative cells.

The process of angiogenesis is initiated by tissue hypoxia and the release of pro-angiogenic mediators such as vascular endothelial growth factor (VEGF) and fibroblast growth factor (FGF). These factors activate endothelial cells, causing them to proliferate and migrate toward the injured tissue. As endothelial sprouts extend, they form new capillary loops through branching and interconnection processes known as anastomosis.

Pericytes, which are contractile cells surrounding endothelial cells, are recruited to strengthen and stabilize the newly formed blood vessels. The maturation of these vessels further involves the recruitment of smooth muscle cells and the deposition of basement membrane components such as collagen type IV and laminin, which provide structural support and stability to the vascular network.

The significance of angiogenesis in wound healing is extremely important. In the absence of sufficient blood supply, wounds cannot progress normally through the healing stages, resulting in delayed recovery or impaired healing. Angiogenesis is also essential for the development of granulation tissue, which is a major component of tissue repair. Moreover, abnormal regulation of angiogenesis may contribute to pathological conditions such as chronic wounds, where persistent inflammation and defective blood vessel formation prevent proper healing.

Fibroplasia

Fibroplasia refers to the proliferation and migration of fibroblasts and is a vital process in tissue repair and regeneration during wound healing. Fibroblasts, the primary cells involved in fibroplasia, are activated by growth factors such as transforming growth factor-beta (TGF-β) and platelet-derived growth factor (PDGF), which are secreted by platelets, macrophages, and other cells following tissue injury.

Once activated, fibroblasts produce and deposit collagen, especially type III collagen, which provides structural support to the healing tissue. This early collagen formation contributes to the development of granulation tissue, an essential stage of wound healing characterized by newly formed blood vessels, fibroblasts, and inflammatory cells. Granulation tissue acts as a framework for tissue repair and supports the later deposition of collagen fibers.

As healing continues, the initially formed type III collagen is gradually replaced by type I collagen, which possesses greater tensile strength and durability. This collagen remodeling process is necessary for scar maturation and strengthening, ultimately helping restore tissue structure and function.

Fibroplasia also contributes to wound contraction, a mechanism controlled by myofibroblasts, which are specialized fibroblasts with contractile abilities. These cells help reduce wound size by pulling the wound edges closer together, thereby promoting wound closure and epithelialization.

FACTORS AFFECTING WOUND HEALING

Wound healing is a highly coordinated and dynamic process that depends on the interaction of several cellular and molecular mechanisms. Although the human body has a remarkable capacity for repair and regeneration, multiple factors can influence the efficiency and outcome of healing. These factors are generally classified into host-related factors, environmental factors, and wound-related factors.

Host-related factors such as age, nutritional condition, and chronic illnesses greatly affect the body's healing capacity. Environmental influences including infections, medications, smoking, obesity, and lifestyle habits can also alter wound healing outcomes. Furthermore, wound-specific characteristics such as wound size, depth, location, and the quality of wound care practices significantly influence the healing process. Understanding these factors is essential for clinicians to improve wound management and achieve successful healing outcomes.

1. *Host-Related Factors*

Host-related factors, including age, nutritional status, and chronic diseases, have a major influence on wound healing. These conditions can alter the body's ability to generate an effective healing response, thereby affecting the speed and quality of recovery.

a) ***Age***

Increasing age is associated with several physiological and molecular changes that negatively affect wound healing. Aging skin undergoes structural alterations such as thinning of the epidermis and dermis, reduction in collagen content, and changes in the extracellular matrix. These modifications decrease the skin's tensile strength and elasticity, impairing effective wound closure.

At the cellular and molecular level, aging reduces the proliferation and migration of keratinocytes and fibroblasts, which are essential for re-epithelialization and collagen formation. Elderly individuals also experience a persistent low-grade inflammatory condition known as "inflammaging," which prolongs the inflammatory phase and delays progression to the proliferative stage of healing.

Potential therapeutic approaches in elderly patients may focus on enhancing keratinocyte and fibroblast function, regulating inflammation, and improving extracellular matrix formation.

b) ***Nutrition***

Adequate nutrition is fundamental for proper wound healing because it supplies the nutrients necessary for tissue repair and regeneration. Protein is essential for collagen synthesis, while amino acids such as arginine and glutamine support fibroblast growth and activity.

Vitamins, particularly vitamin C (ascorbic acid), are important cofactors in collagen synthesis and also possess antioxidant properties that protect tissues from oxidative stress, which can otherwise impair healing. Zinc is another vital micronutrient involved in cell proliferation, protein synthesis, and immune system function. Deficiencies in these nutrients can significantly delay wound healing.

Therapeutic interventions may include supplementation with essential amino acids, vitamins, and minerals to support collagen production and immune responses.

c) ***Chronic Diseases***

Chronic conditions such as diabetes mellitus, peripheral vascular disease, and autoimmune disorders can severely impair wound healing at the molecular level. In diabetes, persistent hyperglycemia leads to the formation of advanced glycation end products (AGEs), which interfere with collagen synthesis and collagen cross-linking, thereby reducing wound tensile strength and delaying tissue repair.

Hyperglycemia also negatively affects endothelial cell function and decreases capillary density, resulting in reduced blood circulation and inadequate oxygen supply to the wound area. Peripheral vascular disease worsens these conditions by further restricting blood flow to the tissues. In autoimmune diseases, abnormal immune regulation may cause persistent inflammation, which delays the healing process. Therapeutic strategies for chronic diseases may therefore focus on controlling blood glucose levels, enhancing circulation, and regulating immune responses to improve wound healing.

2. ***Environmental Factors***

Environmental influences such as infection, medications, smoking, obesity, and lifestyle habits can significantly interfere with the wound healing process. These factors may create unfavorable conditions for tissue repair, leading to delayed healing or the development of complications.

a) ***Infection***

Infection is one of the most important factors that can severely impair wound healing at the molecular level. When a wound becomes infected, microorganisms such as bacteria and fungi, along with their toxic byproducts like lipopolysaccharides (LPS) and exotoxins, enter the wound environment. These substances trigger a strong inflammatory response characterized by the release of pro-inflammatory cytokines and chemokines, including interleukin-1β and tumor necrosis factor-alpha (TNF-α). Prolonged inflammation delays the transition from the inflammatory phase to the proliferative phase, during which fibroblasts migrate to the wound site and begin synthesizing collagen and extracellular matrix components. Some pathogens may also directly disrupt cellular functions essential for healing. For example, certain bacteria release proteolytic enzymes that degrade extracellular matrix proteins, thereby impairing tissue remodeling and repair.

Potential therapeutic approaches for infected wounds include the use of antimicrobial agents to eliminate pathogens, anti-inflammatory medications to regulate excessive inflammation, and growth factors or regenerative therapies to promote tissue repair. Understanding the molecular effects of infection is essential for developing effective wound management strategies.

b) ***Medication***

Certain medications can interfere with wound healing by affecting molecular pathways involved in inflammation and tissue repair. Corticosteroids, which are commonly prescribed for their anti-inflammatory effects, can suppress immune responses and reduce inflammation necessary for normal wound healing. These drugs influence inflammatory mediators such as interleukins and tumor necrosis factor-alpha (TNF-α).

Similarly, immunosuppressive drugs used in organ transplantation can impair healing by weakening the body's defense mechanisms and reducing the immune system's ability to initiate tissue repair. Many of these medications act by targeting immune cells, especially T lymphocytes, to prevent transplant rejection.

Future therapeutic approaches may involve treatments that carefully regulate immune responses while still allowing an appropriate inflammatory reaction necessary for healing. A detailed understanding of the molecular effects of these medications is important for improving healing outcomes in patients who require long-term drug therapy.

c) ***Smoking***

Smoking has a major negative impact on wound healing, mainly because of its effects on blood vessels and inflammatory responses. Nicotine, one of the primary substances found in cigarette smoke, acts on nicotinic acetylcholine receptors (nAChRs) located on fibroblasts, endothelial cells, and immune cells involved in wound repair.

Activation of these receptors causes vasoconstriction, which reduces blood flow to the wound site and limits the supply of oxygen and nutrients needed for tissue repair and cellular metabolism. Nicotine also alters inflammatory responses by affecting the production of inflammatory cytokines such as interleukins and TNF-α. Long-term exposure to nicotine can lead to chronic inflammation and impaired immune function, further delaying healing.

Additionally, nicotine directly inhibits collagen synthesis by fibroblasts, reducing tissue strength and slowing tissue repair. Understanding the molecular mechanisms associated with smoking-related wound impairment is important for developing targeted therapies and improving healing outcomes in smokers.

d) ***Obesity***

Obesity can adversely affect wound healing through several molecular and physiological mechanisms, particularly chronic inflammation and vascular dysfunction. Excess adipose tissue produces inflammatory cytokines such as TNF-α and interleukin-6 (IL-6), contributing to a persistent low-grade inflammatory state. This chronic inflammation can delay the progression from the inflammatory stage to the proliferative phase of wound healing, thereby impairing tissue repair.

Obesity is also strongly associated with insulin resistance, which further worsens inflammation and negatively impacts healing. Adipose tissue secretes biologically active substances known as adipokines, including leptin and adiponectin, which influence immune responses, angiogenesis, and tissue repair processes.

Furthermore, obesity is linked with impaired vascular function, including endothelial dysfunction and decreased microvascular circulation. These abnormalities reduce oxygen and nutrient delivery to the wound site, thereby slowing the healing process. Understanding these molecular and physiological mechanisms is essential for developing effective interventions aimed at improving wound healing outcomes in obese individuals.

e) ***Lifestyle Factors***

Several lifestyle-related factors, such as excessive alcohol intake, psychological stress, and lack of physical activity, can negatively influence wound healing at the molecular level. Excessive alcohol consumption disrupts the balance between pro-inflammatory and anti-inflammatory cytokines, resulting in prolonged inflammation and delayed healing. Alcohol can also weaken immune cell function and reduce collagen production, thereby impairing tissue repair.

Chronic stress affects wound healing by disturbing the hypothalamic-pituitary-adrenal (HPA) axis, which leads to increased secretion of stress hormones such as cortisol. Elevated cortisol levels suppress immune responses and delay tissue regeneration. Similarly, physical inactivity may result in muscle wasting and poor circulation, reducing the delivery of oxygen and nutrients required for effective wound healing. Understanding the molecular mechanisms associated with these lifestyle factors is important for developing therapeutic strategies that improve healing outcomes.

3. ***Wound-Specific Factors***

Wound-related factors, including wound size, depth, location, and the quality of wound care practices, are major determinants of the healing process. Proper evaluation and management of these factors are essential for achieving effective wound healing and preventing complications.

a) ***Wound Characteristics***

Characteristics of the wound, such as its size, depth, and anatomical location, can significantly affect the molecular and cellular mechanisms involved in healing. Large wounds require greater tissue regeneration and are often associated with stronger inflammatory responses. Growth factors such as transforming growth factor-beta (TGF-β) are important molecular mediators that promote cell proliferation and extracellular matrix formation in larger wounds.

Wound depth also influences the extent of tissue damage and the intensity of inflammation. Deep wounds generally require increased collagen deposition and enhanced angiogenesis to restore tissue integrity. Molecular mediators such as vascular endothelial growth factor (VEGF) stimulate the formation of new blood vessels necessary for healing deep wounds.

The location of the wound is another important factor, as wounds occurring in areas with limited blood supply may heal more slowly. Local blood flow and immune regulation are therefore important determinants of healing in such regions. Understanding these molecular mechanisms can assist in designing targeted therapeutic approaches for different wound types and locations.

b) ***Wound Care Practices***

Appropriate wound care practices are essential for promoting successful healing and reducing the risk of infection or delayed recovery. Important wound management strategies include wound cleansing, removal of dead tissue (debridement), and the selection of suitable dressings.

Growth factors such as platelet-derived growth factor (PDGF) play a major role in wound care by stimulating cellular proliferation and angiogenesis. Debridement helps remove necrotic tissue and other barriers that interfere with healing while also stimulating the release of growth factors necessary for tissue repair.

Modern wound dressings help maintain a moist environment favorable for healing and may contain bioactive substances such as collagen or growth factors that further support tissue regeneration. Understanding these molecular targets has contributed to the development of advanced wound care products and improved treatment strategies.

WOUND HEALING TECHNIQUES AND INTERVENTIONS

Wound healing is a complex and continuously evolving process involving overlapping stages such as inflammation, proliferation, and remodeling. Proper wound management is essential to support tissue repair and minimize complications. A variety of treatment methods and interventions are available, ranging from basic wound care products to advanced surgical procedures and modern regenerative technologies.

1. *Dressings and Wound Care Products*

Dressings are one of the most important components of wound management. They protect the wound from external contamination and maintain a moist environment that supports healing. Different types of dressings are available depending on the nature and severity of the wound.

a) ***Gauze Dressings***

Gauze dressings are commonly used for wounds producing moderate to heavy exudate. They provide protection to the wound and may also be impregnated with antimicrobial substances to reduce the risk of infection.

b) ***Hydrocolloid Dressings***

Hydrocolloid dressings contain gel-forming materials that absorb wound exudate and facilitate autolytic debridement. These dressings are generally suitable for wounds with minimal to moderate exudate.

c) ***Foam Dressings***

Foam dressings are highly absorbent and provide cushioning to the wound area, making them ideal for wounds with heavy exudate.

d) ***Alginate Dressings***

Alginate dressings are derived from seaweed fibers and possess high absorbent capacity. They are especially useful in wounds with significant exudate production.

2. *Surgical Interventions*

Surgical procedures are often required in wounds that are severe, non-healing, or prone to complications. Common surgical interventions include the following:

a) ***Debridement***

Debridement refers to the removal of necrotic tissue, foreign material, and infected tissue from the wound bed. This procedure promotes healing by eliminating barriers to tissue regeneration and creating a healthier environment for the growth of new tissue.

b) ***Skin Grafting***

Skin grafting is a surgical procedure in which healthy skin is transplanted from one part of the body to another to cover a wound. This technique is commonly used for wounds that are extensive, deep, or associated with exposed bone, tendon, or other underlying structures. Skin grafting helps promote wound closure, protect underlying tissues, and improve functional and cosmetic outcomes.

c) ***Flap Reconstruction***

Flap reconstruction is a surgical method in which skin along with its underlying tissue and blood supply is transferred to cover a wound defect. This procedure is particularly useful in complex wounds or in situations where local blood circulation is inadequate. Because the flap maintains its own blood supply, it provides improved tissue viability and enhances wound healing in compromised areas.

3. *Emerging Technologies*

Recent advancements in medical technology have introduced several promising approaches for improving wound healing and tissue regeneration. Some of these innovative therapies include:

a) ***Stem Cell Therapy***

Stem cell therapy has gained significant attention because stem cells possess the ability to differentiate into multiple cell types involved in tissue repair. These cells can promote regeneration, reduce inflammation, and enhance the healing process by replacing damaged tissues and stimulating repair mechanisms.

b) ***Growth Factor Therapy***

Growth factor therapy involves the use of biologically active substances such as platelet- derived growth factor (PDGF) and transforming growth factor-beta (TGF-β). These growth factors stimulate cellular proliferation, collagen synthesis, angiogenesis, and granulation tissue formation, thereby accelerating tissue repair and wound healing.

c) ***Negative Pressure Wound Therapy (NPWT)***

Negative Pressure Wound Therapy (NPWT) involves applying controlled negative pressure to the wound surface using a specialized dressing system. This technique promotes granulation tissue formation, reduces edema, removes excess wound exudate, and decreases bacterial contamination, thereby improving the wound healing environment.

Although these emerging technologies show considerable potential, additional clinical research is still required to establish their long-term effectiveness, safety, and practical applications in routine wound care.

CHRONIC WOUND MANAGEMENT

Chronic wounds represent a major challenge in healthcare and often require a multidisciplinary approach for effective treatment and management. These wounds are characterized by prolonged healing duration and failure to heal within an expected time period, usually due to underlying systemic diseases or local factors that interfere with normal healing mechanisms.

Chronic wounds are wounds that do not progress through the normal phases of healing in a timely and organized manner. They are generally classified according to their underlying causes, including pressure ulcers, diabetic foot ulcers, venous ulcers, and arterial ulcers. Common features of chronic wounds include:

- Presence of necrotic tissue
- Persistent or prolonged inflammation
- Delayed or impaired healing
- Recurrence or non-healing despite proper treatment

1. *Challenges in Chronic Wound Healing*

Chronic wounds create multiple difficulties in patient management and healing, including:

Infection

Chronic wounds are highly susceptible to infection because of necrotic tissue accumulation and impaired immune function.

Impaired Healing

These wounds frequently remain in the inflammatory phase and fail to advance properly into the proliferative and remodeling stages necessary for tissue repair.

Pain

Persistent pain is a common feature of chronic wounds and can significantly affect the patient's quality of life, making effective pain management essential.

Economic Burden

Management of chronic wounds is associated with high healthcare costs, including expenses related to dressings, medications, hospitalization, and repeated healthcare visits.

2. *Multidisciplinary Approaches to Chronic Wound Care*

Due to the complexity of chronic wounds, effective management requires collaboration among healthcare professionals from different specialties. A multidisciplinary approach may include:

Wound Care Specialists

Healthcare professionals such as nurses, nurse practitioners, and physicians specialized in wound management who provide comprehensive wound assessment and treatment.

Podiatrists

Foot care specialists who identify and manage foot deformities or conditions contributing to chronic wounds, especially in diabetic patients.

Vascular Surgeons

Specialists who evaluate and treat vascular disorders that impair blood flow and delay wound healing.

Infectious Disease Specialists

Experts who diagnose and manage infections complicating chronic wounds.

Nutritionists

Healthcare professionals who assess nutritional deficiencies and provide dietary interventions necessary to support tissue repair and healing.

The aim of a multidisciplinary approach is to identify and treat the underlying causes of the wound, optimize the healing process, and prevent complications or recurrence. Overall, chronic wound management requires a comprehensive and coordinated treatment strategy involving multiple healthcare disciplines to achieve successful outcomes.

WOUND HEALING IN SPECIAL POPULATIONS

Wound healing is a highly complex process that can be significantly influenced by age, systemic diseases, and individual patient characteristics. Certain special populations, including pediatric patients, geriatric individuals, and patients suffering from conditions such as diabetes mellitus and autoimmune diseases, require unique considerations in wound care management to ensure effective healing and improved clinical outcomes.

. *Pediatric Wound Healing*

Wound healing in children is generally rapid and highly efficient because young tissues possess strong regenerative capabilities. The inflammatory response in pediatric wounds is usually shorter in duration and less severe than in adults, allowing faster resolution of inflammation and minimizing scar formation. However, children are more susceptible to certain injuries such as abrasions, cuts, and sports-related wounds. These injuries require proper cleaning, dressing, and infection prevention measures to ensure effective healing and avoid complications.

2. *Geriatric Wound Healing*

Advancing age is associated with several physiological changes that can negatively affect wound healing. Elderly individuals commonly experience reduced skin elasticity, thinning of the skin, and decreased collagen content, all of which delay wound closure and tissue repair. Age-related alterations in immune function may also impair the inflammatory response, leading to prolonged inflammation and slower healing.

Furthermore, chronic diseases frequently present in older adults, such as diabetes mellitus and peripheral vascular disease, further complicate the healing process and increase the risk of chronic wounds including pressure ulcers and venous ulcers. Therefore, wound management in geriatric patients requires careful monitoring and comprehensive treatment strategies.

3. *Wound Healing in Patients with Specific Conditions Diabetes*

Diabetes mellitus is a major factor contributing to impaired wound healing because of its adverse effects on circulation and immune function. Persistent hyperglycemia damages blood vessels and peripheral nerves, resulting in poor blood supply and reduced sensation, especially in the extremities.

Diabetic foot ulcers are among the most common complications associated with diabetes and require meticulous wound care, pressure offloading, infection control, and proper blood glucose management to promote healing and prevent complications such as gangrene or amputation.

Autoimmune Diseases

Patients suffering from autoimmune disorders such as rheumatoid arthritis and systemic lupus erythematosus may experience delayed wound healing due to chronic inflammation and the use of immunosuppressive medications. These medications, while necessary to control the autoimmune condition, can suppress immune responses essential for tissue repair.

Management of wounds in such patients requires a balanced approach that simultaneously controls the underlying autoimmune disease while supporting wound healing and preventing infection.

In all special populations, a multidisciplinary approach is necessary for effective wound management. This team may include wound care specialists, nurses, dietitians, physiotherapists, and other healthcare professionals. Proper wound assessment, treatment of underlying medical conditions, nutritional optimization, and appropriate wound care interventions are essential to achieve successful healing outcomes.

BIOMATERIALS AND TISSUE ENGINEERING IN WOUND HEALING

Biomaterials and tissue engineering have significantly advanced modern wound management by introducing innovative methods to promote tissue repair and regeneration. These approaches utilize scaffolds, matrices, and bioactive substances to create an environment favorable for cellular growth and tissue formation, thereby improving wound healing outcomes.

1. *Use of Scaffolds and Matrices in Wound Repair*

Scaffolds and matrices provide structural support for cells and promote cell attachment, migration, proliferation, and differentiation during wound healing. Natural polymers such as collagen and hyaluronic acid closely resemble the native extracellular matrix (ECM), thereby enhancing cellular adhesion and tissue regeneration.

Synthetic polymers, including polyethylene glycol (PEG) and poly lactic-co-glycolic acid (PLGA), offer customizable physical and mechanical properties suitable for different wound- healing applications. Composite materials that combine natural and synthetic polymers provide improved mechanical strength and biological activity, supporting tissue repair more effectively.

Advanced fabrication techniques such as electrospinning and three-dimensional (3D) printing allow the production of scaffolds with tailored structures and mechanical characteristics. These scaffolds can also be engineered to degrade gradually over time, enabling proper tissue integration and regeneration.

2. *Tissue Engineering Approaches for Skin Regeneration*

Tissue engineering provides promising solutions for skin regeneration, particularly in extensive skin loss and chronic wounds. One important approach involves cell-seeded scaffolds, in which cells such as keratinocytes and fibroblasts are cultured onto scaffold materials to enhance tissue formation and wound closure.

Decellularized matrices, which preserve the natural extracellular matrix structure, serve as templates for cellular infiltration and tissue regeneration. In addition, bioprinting technologies enable precise control of scaffold architecture and cell placement, allowing the creation of complex skin substitutes.

Growth factors such as platelet-derived growth factor (PDGF) and transforming growth factor- beta (TGF-β) can also be incorporated into scaffolds to stimulate cell proliferation, extracellular matrix production, and tissue repair. Stem cells are another promising component of skin tissue engineering because of their ability to differentiate into multiple cell types involved in skin regeneration and healing.

3. *Bioactive Materials and Their Role in Promoting Wound Healing*

Bioactive materials such as growth factors, extracellular vesicles, and antimicrobial peptides play a significant role in enhancing wound healing. Growth factors support angiogenesis, regulate inflammation, and stimulate cellular proliferation and migration, thereby accelerating tissue repair.

Extracellular vesicles contain biologically active molecules capable of influencing cellular behavior and promoting tissue regeneration. Antimicrobial peptides help eliminate pathogens, reducing the risk of infection and creating a favorable environment for healing.

These bioactive substances can be incorporated into scaffolds or directly applied to wounds to improve healing outcomes. Controlled drug delivery systems such as hydrogels and nanoparticles allow sustained release of therapeutic molecules, ensuring prolonged activity and enhanced wound repair.

FUTURE DIRECTIONS AND INNOVATIONS IN WOUND HEALING

Research in wound healing continues to advance rapidly, with modern innovations and technologies focused on improving healing outcomes in both acute and chronic wounds. Current developments include biological therapies, regenerative medicine, smart wound dressings, gene therapy, nanotechnology, and bioinformatics, all of which offer promising opportunities for enhancing wound care.

1. *Advancements in Wound Healing Research Biological Therapies*

Biological therapies have emerged as promising approaches in wound management. Stem cell therapy has demonstrated potential in enhancing tissue regeneration, reducing inflammation, and accelerating the healing process. Similarly, growth factors such as platelet-derived growth factor (PDGF) and fibroblast growth factor (FGF) are being extensively studied because of their ability to stimulate cell proliferation, angiogenesis, and tissue repair.

Regenerative Medicine

Regenerative medicine and tissue engineering provide innovative methods for restoring damaged tissues. Techniques such as skin substitutes and three-dimensional (3D) bioprinting aim to create tissue structures that closely resemble natural human skin. These engineered tissues help improve integration with surrounding tissues and promote faster wound closure and functional recovery.

Smart Wound Dressings

Advanced smart wound dressings are being developed with the capability to monitor important wound parameters such as pH, temperature, and moisture levels. These dressings can provide real-time information about the healing status of the wound and help in the early detection of complications such as infection or delayed healing.

Gene Therapy

Gene therapy represents another emerging area in wound healing research. This approach involves delivering therapeutic genes to wound tissues in order to enhance biological processes such as angiogenesis, collagen synthesis, and extracellular matrix formation. Gene-based therapies may significantly improve cellular responses required for tissue repair.

2. *Potential Breakthroughs in Wound Healing Technology Nanotechnology*

Nanotechnology has opened new possibilities in wound care through the use of nanoparticles and nanofibers in dressings and scaffolds. These nanomaterials can improve mechanical strength, allow controlled drug delivery, and enhance cell adhesion and proliferation, thereby supporting tissue regeneration and faster healing.

Bioinformatics

Advances in bioinformatics and computational analysis have enabled researchers to better understand the complex molecular pathways involved in wound healing. This deeper understanding supports the development of targeted therapies that may accelerate wound closure and improve clinical outcomes.

Advanced Imaging Techniques

Modern imaging technologies such as multiphoton microscopy and optical coherence tomography provide high-resolution visualization of wounds and surrounding tissues. These non-invasive imaging techniques allow continuous monitoring of wound progression and early identification of complications including infection or tissue damage.

3. *Challenges and Opportunities in Improving Wound Care Outcomes Chronic Wounds*

Chronic wounds, including diabetic foot ulcers and pressure ulcers, remain one of the greatest challenges in wound care. Effective management requires addressing the underlying causes such as impaired circulation, infection, and delayed tissue repair in order to improve healing outcomes.

Infection Control

Prevention and management of wound infections are essential for successful healing. Ongoing research is focused on developing newer antimicrobial agents, advanced dressings, and innovative infection-control strategies to minimize complications and promote tissue repair.

Patient-Centered Care

Patient-centered wound care focuses on individual patient needs, preferences, and overall quality of life. Educating patients, involving them actively in their treatment, and providing emotional and social support are important aspects of improving wound healing outcomes and long-term care.

CONCLUSION

In conclusion, a thorough understanding of the complex mechanisms involved in wound healing is essential for effective wound management and patient care. This review highlights the importance of considering multiple factors that influence healing outcomes, including patient-related, local, and systemic factors. It also emphasizes the role of advanced techniques and interventions such as biomaterials, tissue engineering, and regenerative medicine in promoting tissue repair and regeneration.

Management of chronic wounds continues to be a major clinical challenge and requires multidisciplinary collaboration along with innovative therapeutic strategies to improve healing outcomes. Special populations, including pediatric patients, geriatric individuals, and patients with chronic diseases, require individualized approaches because of their unique healing characteristics and challenges.

Overall, continued research and technological advancement in wound healing are essential for improving clinical practice and patient outcomes. By exploring emerging technologies, identifying potential breakthroughs, and addressing existing challenges, significant progress can be achieved in the field of wound care, ultimately benefiting patients around the world.

REFERENCES

1. Singer AJ, Clark RA. Cutaneous wound healing. *N Engl J Med.*, 1999; 341(10): 738– 746.
2. Carmeliet P, Jain RK. Angiogenesis in cancer and other diseases. *Nature*, 2000; 407(6801): 249–257.
3. Frantz RA, Castellani LW, Wahl LM, Waldschmidt TJ. Cytokines in wound healing: The role of cytokine and anti-inflammatory agents in the repair response. *J Burn Care Rehabil*, 1993; 14(1): 6–10.
4. Lazarus GS, Cooper DM, Knighton DR, Margolis DJ, Pecoraro RE, Rodeheaver G, Robson MC. Definitions and guidelines for assessment of wounds and evaluation of healing. *Wound Repair Regen*, 1994; 2(3): 165–170.
5. Bowler PG, Duerden BI, Armstrong DG. Wound microbiology and associated approaches to wound management. *Clin Microbiol Rev.*, 2001; 14(2): 244–269.
6. Ashcroft GS, Mills SJ. Androgen receptor-mediated inhibition of cutaneous wound healing. *J Clin Invest*, 2002; 110(5): 615–624.
7. Gore DC, Chinkes DL, Hart DW, Wolf SE, Herndon DN, Sanford AP. Hyperglycemia exacerbates muscle protein catabolism in burn-injured patients. *Crit Care Med.*, 2002; 30(11): 2438–2442.
8. Schultz GS, Davidson JM, Kirsner RS, Bornstein P, Herman IM. Dynamic reciprocity in the wound microenvironment. *Wound Repair Regen*, 2011; 19(2): 134–148.
9. Gottrup F, Apelqvist J. Present and new techniques and devices in the treatment of diabetic foot ulcers: A critical review of evidence. *Diabetes Metab Res Rev.*, 2012; 28(1): 64–71.
10. Marston WA. Dermagraft, a bioengineered human dermal equivalent for the treatment of chronic non-healing diabetic foot ulcers. *Expert Rev Med Devices*, 2004; 1(1): 21–31.
11. Sibbald RG, Woo KY. The biology of chronic foot ulcers in persons with diabetes. *Diabetes Metab Res Rev.*, 2008; 24(1): S30.
12. Vuerstaek JD, Vainas T, Wuite J, Nelemans P, Neumann MH, Veraart JC. State-of-the- art treatment of chronic leg ulcers: A randomized controlled trial comparing vacuum- assisted closure (V.A.C.) with modern wound dressings. *J Vasc Surg.*, 2006; 44(5): 1029–1037.
13. Jeffcoate WJ, Harding KG. Diabetic foot ulcers. *Lancet*, 2003; 361(9368): 1545–1551.
14. Frykberg RG, Banks J. Challenges in the treatment of chronic wounds. *Adv Wound Care (New Rochelle)*, 2015; 4(9): 560–582.
15. Bistrian BR. Wound healing and nutrition. *World J Surg*, 1999; 23(6): 545–550.
16. Barrientos S, Stojadinovic O, Golinko MS, Brem H, Tomic-Canic M. Growth factors and cytokines in wound healing. *Wound Repair Regen*, 2008; 16(5): 585–601.
17. Mirza RE, Koh TJ. Contributions of cell subsets to cytokine production during normal and impaired wound healing. *Cytokine*, 2015; 71(2): 409–412.
18. Lucas T, Waisman A, Ranjan R, et al. Differential roles of macrophages in diverse phases of skin repair. *J Immunol*, 2010; 184(7): 3964–3977.
19. Golebiewska EM, Poole AW. Platelet secretion: From haemostasis to wound healing and beyond. *Blood Rev.*, 2015; 29(3): 153–162.
20. Italiano JE, Richardson JL, Patel-Hett S, et al. Angiogenesis is regulated by a novel mechanism: Pro- and antiangiogenic proteins are organized into separate platelet α- granules and differentially released. *Blood*, 2008; 111(3): 1227–1233.
21. Eming SA, Martin P, Tomic-Canic M. Wound repair and regeneration: Mechanisms, signaling, and translation. *Sci Transl Med.*, 2014; 6(265): 265sr6.
22. Martin P, Nunan R. Cellular and molecular mechanisms of repair in acute and chronic wound healing. *Br J Dermatol*, 2015; 173(2): 370–378.
23. Werner S, Grose R. Regulation of wound healing by growth factors and cytokines. *Physiol Rev.*, 2003; 83(3): 835–870.
24. Sen CK, Gordillo GM, Roy S, et al. Human skin wounds: A major and growing threat to public health and the economy. *Wound Repair Regen*, 2009; 17(6): 763–771.
25. *International Journal of Scientific Development and Research (IJSDR).* Available from: www.ijsdr.org