

Review Article

Comprehensive Review of Traditional to Advanced Wound Care: Classification, Healing Stages, and Technological Progress

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Effective wound care management necessitates thorough knowledge of wounds, their classification and appropriate treatment strategies to promote optimal wound healing. Wounds are categorised based on exposure to the environment, recovery time and contamination. These classifications aid healthcare professionals in selecting appropriate strategic treatment approaches and choosing suitable wound dressings to support rapid wound healing. Cotton gauze, bandages, plasters, and lint have traditionally served as wound care dressings. They primarily functioned as protective barriers that covered the wound but failed to maintain a moist environment, often resulting in direct adhesive contact with the wound surface, required frequent changes of wound dressings, and contributed to serious infection risk. To overcome these challenges, technological advancements have been incorporated into wound care materials, such as foam dressings, film dressings, hydrocolloids, hydrogels, nano-scaffolds, and nanoparticle-based dressings, to hasten the wound healing process. This article reviews types of wounds based on exposure to the environment, recovery time, and contamination, as well as conventional methods of wound management and recent innovations in dressing materials, highlighting their importance in enhancing healing processes and improving overall patient care.

Introduction

As the largest organ of the human body, the skin is a highly sophisticated and multilayered structure that functions to safeguard the internal tissues from mechanical deformation, ultraviolet radiation, extreme environmental heat, and contagious infections [1]. Because of the continuous exposure to the environment, it is highly prone to injury, which significantly impacts both patient well-being and the healthcare system. As a vital organ, the skin also influences the sophisticated healing process [2], which involves the activation of numerous cellular components and intricate signalling cascades. Any disturbance in the structural integrity of living tissue is considered a wound. The skin contributes significantly to safeguarding the human internal anatomical structures by covering its hydrated internal organs from the dehydrating external environment [3]. Wound healing is an intricate and effective process, and a solid understanding of its physiological foundations is essential for effectively managing chronic wounds. Comprehending wound

healing at the biochemical, physiological, cellular, and molecular levels equips clinicians with a structured framework to guide clinical decisions and enhance the healing response [4]. Wound healing is a highly coordinated process driven by cellular, molecular, and biochemical mechanisms and is classically categorised into four sequential overlapping phases: haemostasis, inflammation, proliferation, and remodelling [5]. Emerging therapeutic strategies in wound management, particularly those based on biomaterials, nanoparticles, and biomimetic proteases, hold significant promise to enhance wound care and accelerate the healing process [6].

Wound care management is a crucial core component of the healthcare system, as wounds vary significantly in cause, severity, and healing potential, necessitating proper classification and tailored treatment strategies [7]. Wounds are commonly classified based on factors such as duration, depth, and aetiology, which helps guide clinical decision-making and selection of suitable dressings [8]. Historically, wound care has relied on traditional dressings, such as gauze, cotton wool,

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Table 1: Wound classification based on exposure to the environment and healing recovery

Classification Basis	Types	Description
Exposure to the environment	Closed wound,	Based on whether the skin surface is intact or broken.
	Open wound	
Healing duration	Acute wound, Chronic wound	Based on healing time and the presence of complications.

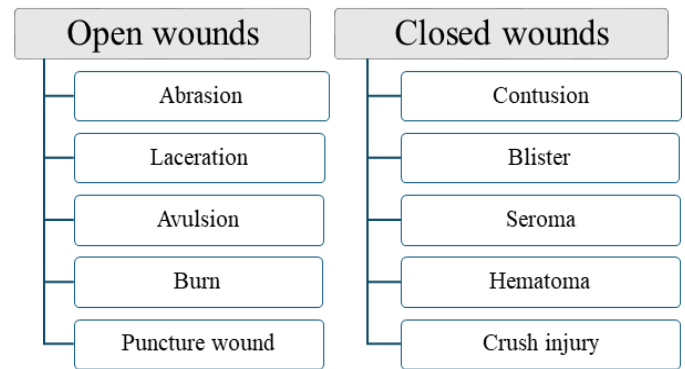
bandages, plasters, and lint, which primarily served to cover wounds, absorb exudate, and offer basic protection [9]. While these conventional dressings were affordable and widely accessible, they often failed to maintain an optimal healing environment, lacked antimicrobial protection, and could cause pain or tissue damage during dressing changes. Innovations in medical science have contributed to the development of modern wound dressings designed to address these limitations. Advanced dressings, including hydrocolloids, foams, hydrogels, and antimicrobial-impregnated materials, promote moisture balance, enhance tissue regeneration, and reduce the infection risk [10]. Modern dressings have incorporated properties including moisture regulation, antimicrobial activity, and enhanced biocompatibility, thereby supporting faster healing and improved patient outcomes [11]. This evolution from conventional to modern wound dressings reflects ongoing efforts to improve healing outcomes, patient comfort, and overall quality of wound care. Wound classification, conventional wound care practices, and emerging advanced dressing technologies collectively provide the foundation for contemporary strategies in effective wound management.

Wound

A wound is any disruption or break in the structural continuity of the skin. Wound management remains a significant challenge for healthcare professionals, as complications associated with wounds can raise the risk of illnesses and death both prior to and following medical treatment [12]. Wounds will occur by chance or through purposeful means (e.g., surgical incision). This will vary in severity from superficial, minor injuries to severe injuries involving deeper, anatomical structures such as muscles, nerves, blood vessels, and bone [13]. The skin is continuously exposed to the environment, and it provides particular challenges in protecting it from injury by cuts, burns, abrasions and traumas. Minor wounds typically heal naturally; serious, untreated wounds carry a risk of bacterial infection [14].

Classification of wounds

Wounds are classified in several ways based on different criteria. They

**Figure 1: Types of open and closed wounds**

are commonly categorised as open or closed according to skin exposure to the external environment and breakage of the skin, and as acute or severe based on their severity and healing duration, as shown in table 1. An open wound is an injury where skin is torn, cut, or punctured because of physical trauma. In contrast, a closed wound results from a blunt force trauma, causing internal damage, such as contusion or bruise, without breaking the skin [15]. Some examples of open and closed wounds are given in figure 1. A closed wound occurs when the underlying tissue is damaged, but the skin surface remains intact, while an open wound exposes the underlying tissue to the environment due to a crack or split in the skin [16]. Abrasion, laceration, avulsion, burn, and puncture wounds are open wound types, and contusion, blister, seroma, hematoma, and crush injury are closed wound types.

An acute wound heals within the expected time without complications [17], whereas a chronic wound develops complications and takes a longer time to heal [18, 19]. Examples for acute and chronic wounds are given in figure 2. Abrasion, avulsion, crush wounds [20], lacerations, missile wounds, and radiation wounds [21] are classified as acute wounds, and vascular ulcers, diabetic ulcers [22], pressure ulcers [23], and ischemic wounds are categorised under chronic wounds. Open and closed wound types are given in table 2 and table 3. Acute and chronic wound types are given in tables 4 and 5.

Wound classification based on contamination

Based on the wound's level of contamination, contemplating wound closure, wounds are classified into four types by the American College of Surgeons. This classification aids healthcare professionals in selecting optimal treatment, infection risk, and wound healing outcomes.

Table 2: Open wound types and classification

Type	Description	Classification
Abrasion	A superficial injury caused by scraping or rubbing of the skin, resulting in pain, discolouration, and minor bleeding.	Linear (scratch) abrasions, patterned abrasions, and grazed or brush abrasions.
Laceration	A tear or cut in the skin caused by blunt force trauma or rough mechanical objects, which is usually associated with pain and bleeding. It is characterised by irregular, torn, or jagged edges, unlike incisions, which have smooth edges.	Not typically subclassified; identified by irregular wound margins.
Avulsion	A severe traumatic injury in which the skin is forcibly torn away from the body, either partially or completely, forming a skin flap or exposing underlying tissues such as muscles, tendons, and bones.	Also referred to as a degloving soft tissue injury.
Burn	Damage to skin tissue caused by heat, chemicals, electricity, or radiation.	First-degree (superficial), second-degree (partial-thickness), third-degree (full-thickness), and fourth-degree burns.
Puncture Wound	A deep and narrow injury caused by penetration of a sharp pointed object such as a nail, animal teeth, tack, or high-pressure injection. These wounds have a severe infection risk.	Types I, II, Type IIIA, Type IIIB, and Type IV are based on depth, contamination, and severity.

Table 3: Closed wound types

Type	Description
Contusion (Bruise)	A bruise, also known as a contusion, results from damage to small blood vessels beneath the skin, leading to tenderness and altered skin colour, often accompanied by soreness and swelling.
Blister	Blisters or boils are fluid-filled pockets that develop due to burns, friction, infections, or skin irritation. These lesions may contain fluid, blood, or pus and can sometimes be associated with itching.
Seroma	A seroma is the accumulation of non-infectious, clear, yellowish, straw-coloured serous fluid within a tissue or body cavity, commonly occurring after surgery or trauma.
Hematoma	A hematoma is the accumulation of clotted or partially clotted blood outside blood vessels, typically within tissues, organs, or body cavities, resulting from ruptured blood vessels due to trauma, injury, or surgical procedures.
Crush Injury	A crush injury is a physical trauma caused by intense external force or pressure applied to a body part, often when it is compressed between heavy objects, leading to damage to blood vessels, muscles, and nerves.

Table 4: Acute-type wounds

Type of Wound	Explanation
Abrasion / Scrapes	Superficial wounds occur when the superficial layer of the skin (epidermis) is removed as a result of friction against a rough surface.
Avulsion / Contusions	Avulsion: Forcible detachment of tissue of the body from its normal position. Contusion: Bruising caused by blunt trauma that damages blood vessels without breaking the skin.
Crush or Cut Wounds	Injuries caused by heavy compression or sharp objects often damage deeper tissues and sometimes bones.
Lacerations	Irregular tears in the skin or tissue caused by blunt trauma or accidents, often with jagged wound edges.
Missile / Velocity Wounds	Wounds caused by high-velocity projectiles such as bullets or fragments that penetrate body tissues.
Radiation Wounds / Ulcers	Tissue injury resulting from exposure to ionising radiation, leading to skin breakdown and ulceration.

Table 5: Chronic type wounds

Type of Wound	Explanation
Venous / Vascular Ulcers	Ulcers caused by chronic venous insufficiency, where blood flow in the veins is impaired, usually affect the lower legs
Diabetic Ulcers	Foot ulcers are commonly seen in people with diabetes due to neuropathy, poor circulation, and increased risk of infection
Pressure Ulcers	Localised damage to the skin and underlying tissues occurs due to sustained pressure, typically affecting areas over bony prominences in patients with limited mobility
Ischemic Wounds	Occur when reduced arterial blood supply causes tissue hypoxia and tissue death, leading to non-healing wounds

Wound classification based on contamination and its explanation is illustrated in figure 3.

There are four categories of wounds based on contamination: Class

I-clean wounds; Class II-clean contaminated wounds; Class III-contaminated wounds; Class IV-dirty, infected wounds.

Class I - Clean wounds

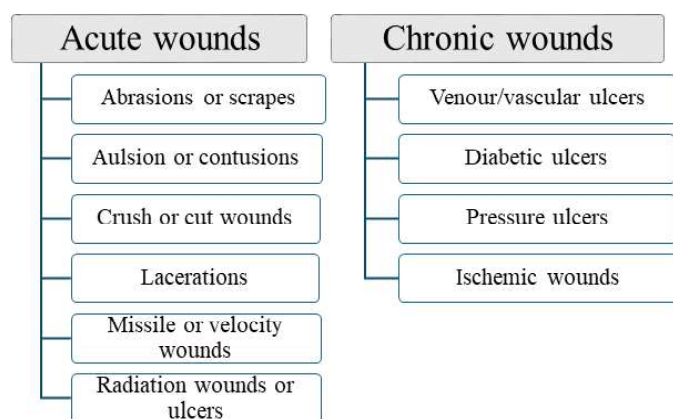
A clean surgical wound shows no evidence of infection or inflammation and is usually closed primarily after surgery [24]. These types of wounds remain confined without entering into the respiratory, gastrointestinal, or genitourinary systems. Clean surgical wounds usually occur during elective or non-traumatic surgical procedures [25], including skin biopsies, laparoscopic surgeries, and certain eye or vascular surgeries.

Class II - Clean contaminated wounds

Surgical wounds that are generally clean and primarily closed but involve entry into the respiratory, gastrointestinal, or genitourinary tracts under aseptic and controlled conditions without significant contamination or spillage of organ contents. These procedures are conducted under sterile conditions; the inclusion of these tracts increases the likelihood of infection compared to clean wounds. Examples of Class II wounds include procedures such as removal of pins and wires, certain chest procedures, ear surgeries, and gynaecological surgeries.

Class III - Contaminated wounds

Typically, open-type injuries occur when foreign objects such as bullets,

**Figure 2: Types of acute and chronic wounds**

knives, or other sharp instruments penetrate the skin, leading to exposure and contamination of the wound. These wounds often involve traumatic penetrating injuries and may result from significant spillage of contents from the gastrointestinal tract into the wound site, particularly when the injury is less than 4–6 hours old. Contaminated wounds may also arise when there is a significant lapse in surgical sterility or the presence of highly inflamed tissue around the surgical site, increasing the risk of infection.

Class IV - Dirty, infected wounds

These are open and already infected wounds which may contain foreign materials such as faecal matter or debris. They are often related to conditions, such as abscess formation or perforation of the bowel, which may result in the presence of pus or faecal contamination, including traumatic wounds with delayed treatment, previously infected surgical wounds, or any wounds exposed to purulent discharge or faecal debris, thereby indicating a high level of microbial contamination.

Wound Healing Process

Wound healing is a convoluted process that incorporates the repair or replacement of injured skin and underlying tissues following damage [26]. It refers to the body's own physiological response, which is activated to maintain the structure and function of the skin after injury [27]. When the protective barrier of the skin is disrupted due to mechanical, chemical, or biological injury, a set of synchronised cellular and molecular processes is initiated to restore the tissue damage. This is a spontaneous process and occurs through highly regulated biochemical mechanisms that involve various types of cells, signalling molecules, and extracellular matrix elements working collectively to rebuild the affected area [28].

In general, wound repair is the natural process of dermal tissue repair through the body's intrinsic regenerative capacity [29]. The healing process begins shortly after injury through the integumentary system, which is characterised by a series of stages aimed at clearing pathogens, closing the wound, and promoting regeneration [30]. Tissue repair is defined by the repair of the affected tissue or, in some instances, the formation of scar tissue, which replaces the affected part. These two processes occur simultaneously, depending on the depth, severity, and

nature of injury.

From a physiological perspective, wound healing can be described as a complex and integrated biological process that occurs in four stages or phases: "haemostasis, inflammation, proliferation, and remodelling". During the first phase, or haemostasis, blood clotting begins, and a clot forms to stop the bleeding. This clot acts as a scaffold for cellular migration [31]. The second phase is characterised by inflammation, where immune cells clean out debris, pathogens, and compromised tissues. The proliferation phase involves granular tissue formation, angiogenesis, fibroblast proliferation, collagen deposition, and re-epithelialisation. This phase restores normal tissues [32]. In the last phase, or remodelling, collagen deposition occurs, and tissues are strengthened to normal or near-normal function, although the healed tissues may not be identical to the original skin tissues [33].

Overall, wound healing can be described as the process of recovery or repair of damaged dermal tissue, which occurs through spontaneous regeneration of dermal tissue components or repair of connective tissue. This highly organised physiological process is critical for survival, as it helps to maintain tissue structure and function [34]. From a research point of view, it is now widely accepted that the process of wound healing is an interactive system, as opposed to a simple process. Interruptions in any of the processes, as a result of various factors such as metabolic diseases, ageing, infections, and defects in signalling pathways, result in impaired healing. Analysing the cellular, molecular, and mechanical processes involved in wound healing is critical for the development of advanced therapeutic interventions.

Wound healing types

Wound healing can also be classified into primary, secondary, and tertiary types, which are illustrated in figure 4.

Clean	Uninfected operative wounds without inflammation; respiratory, alimentary, genital or uninfected urinary tracts are not entered
Clean/contaminated	Operative wounds in the respiratory, alimentary, genital or uninfected urinary tracts are electively entered; without unusual contamination
Contaminated	Open, fresh, accidental wounds, operations with major breaks in sterile technique or gross spillage from the gastrointestinal tract, and incisions in which acute, non-purulent inflammation is encountered
Dirty	Old traumatic wounds with retained devitalized tissue or those that involve existing clinical infection or perforated viscera

Figure 3: Wound classification based on contamination

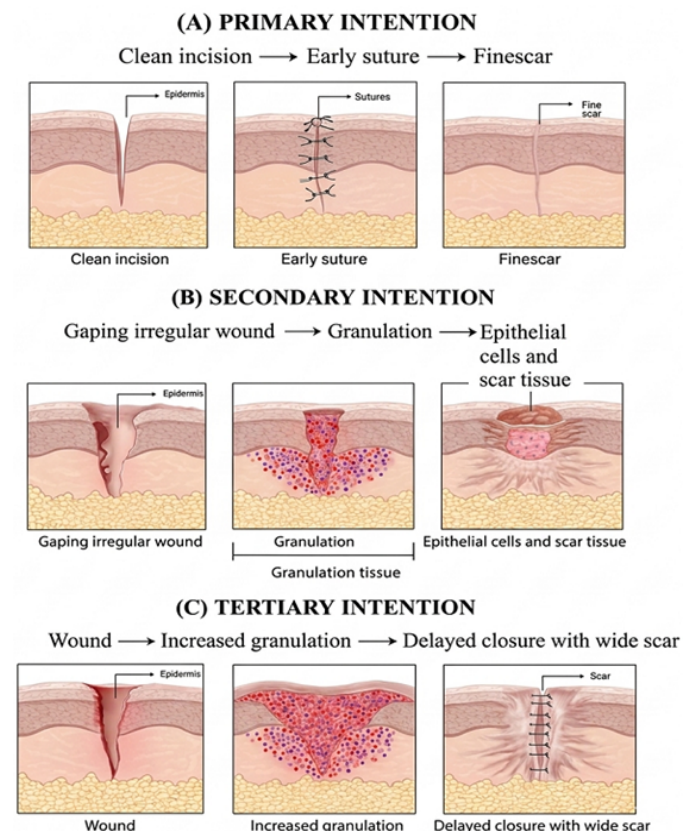


Figure 4: Wound healing types (Reproduced with permission from Ref. [42]. Copyright 2024, American Chemical Society)

Primary healing or primary intention

Primary intention wound healing involves approximation and maintenance of alignment between the wound margins. Primary wound closure is achieved using sutures, staples, adhesive strips, or tissue adhesives [35]. It is commonly applied to clean surgical wounds or minor lacerations with minimal tissue loss, promoting faster healing by reducing the open wound surface and minimising granulation tissue formation. In primary intention wounds, the inflammatory response is minimal, and epithelial cell proliferation occurs quickly to reestablish the skin barrier. Because the wound edges are closely approximated and the risk of contamination is low, this process results in minimal scarring and efficient restoration of normal tissue structure. Therefore, the normal healing of a well-approximated and uninfected wound is typically referred to as primary healing or healing by primary intention [36, 37], and it represents the most rapid and favourable pathway of wound repair.

Secondary healing or secondary intention

Wound healing by secondary intention [36, 37] occurs when the wound edges cannot be brought together due to extensive tissue loss, infection, or other clinical limitations. In such cases, the wound will be allowed to heal on its own by being left open on purpose for granulation tissue formation, wound margin contraction, and gradual re-epithelialisation. This process is typically observed in large traumatic injuries; chronic ulcers, such as diabetic ulcers, vascular ulcers, or pressure ulcers; and in cases of post-surgical wound dehiscence where the wound has reopened due to factors such as contamination, haematoma formation, or excessive mechanical tension. Differing from primary intention healing, the secondary intention comprehends a larger tissue defect and therefore requires a longer healing period, as the wound cavity must be progressively filled with newly formed connective tissue. The prolonged healing time also increases the negative outcomes of microbial contamination and infection. In addition, several systemic and local factors - such as hypoxia, impaired immune function, medication use, poor circulation, or underlying chronic diseases - can further delay the repair process. As

a result, wounds healing by secondary intention are generally more susceptible to delayed healing and complications compared with wounds that can be closed primarily.

Tertiary healing or tertiary intention

Tertiary wound healing, also referred to as delayed primary intention [36,37], is a wound management approach used when there is a high risk of infection or contamination of the wound due to necrotic tissue or when the secondary intention is delayed intentionally. In this method, the wound is initially left open rather than being immediately closed. This allows adequate drainage of exudates and provides time for the removal of contaminants, devitalised tissue, and potential microbial agents through appropriate wound care and therapeutic interventions. During this period, treatments such as debridement, antimicrobial therapy, and proper wound cleaning are applied to create a favourable environment for healing.

Once the wound base becomes clean and viable by controlling the high infection risks, the wound edges are then surgically approximated using sutures, staples, or other closure techniques. Upon completion of closure, the process of healing continues through the mechanisms of primary intention. This process has the advantage of being more efficient. This method is particularly useful in traumatic injuries, contaminated surgical wounds, or wounds with significant tissue damage where immediate closure could increase the likelihood of infection or other complications. By delaying closure until optimal conditions are achieved, tertiary intention healing helps reduce infection risk and improves overall wound healing outcomes.

Wound healing phases

There are 4 phases of wound healing: They are haemostasis, inflammation, proliferation and remodeling as illustrated in figure 5.

Haemostatic phase

Haemostasis will be initiated by the human body immediately after a skin injury to reduce bleeding. The vascular conduits narrow to decrease

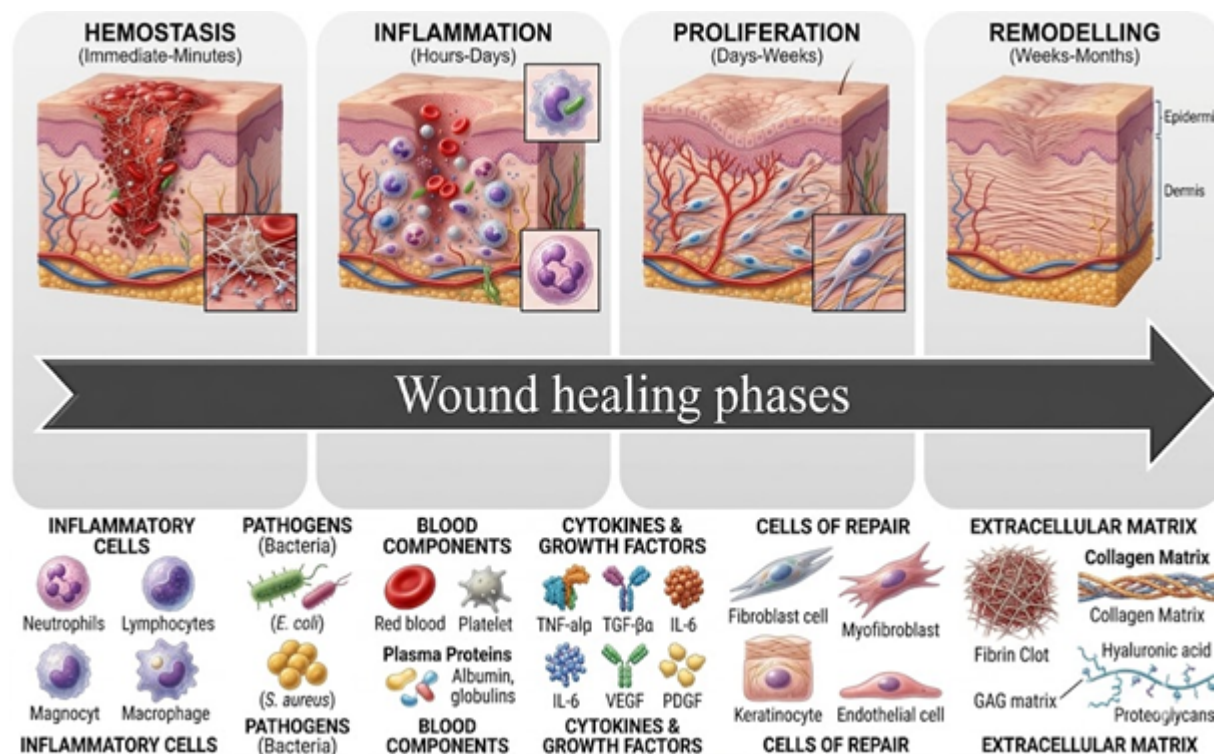


Figure 5: Illustration of wound healing phases

the bleeding, while the damaged conduits will be adhered to by the platelets rapidly for collagen exposure in the extracellular matrix. The activation of platelets induces the release of cytokines, growth factors, and inflammatory mediators, promoting platelet aggregation and initiating both intrinsic and extrinsic clotting pathways. Thrombin is generated during this process, forming a fibrin clot by converting fibrinogen into fibrin that seals the damaged vessels and prevents further bleeding. The clot is strengthened by the accumulation of tissue factor carried by microvesicles from white blood cells that attach to the platelet surface. The fibrin clot forms a temporary haemostatic plug that serves as a reservoir of signalling molecules that initiate the healing cascade. Activated platelets release mediators such as thromboxane A₂ and serotonin, which contribute to vasoconstriction and inflammation. Furthermore, platelets have been shown to secrete important growth factors, like platelet-derived growth factor (PDGF) and transforming growth factor-beta (TGF- β). PDGF is involved in the chemotaxis of fibroblasts, macrophages, neutrophils, and smooth muscle cells towards the site of injury, as well as the proliferation of fibroblasts and smooth muscle cells, thereby preparing the tissue for repair.

TGF- β is involved in the modulation of the wound healing process by attracting macrophages towards the site of injury, which in turn release other cytokines like fibroblast growth factor (FGF), tumour necrosis factor-alpha (TNF-alpha) [1, 35], PDGF, and interleukin-1 (IL-1). It also enhances fibroblast migration and regulates collagen production and collagen breakdown, which are essential for rebuilding the extracellular matrix. Through the combined actions of PDGF and TGF- β , new connective tissue is formed to restore the damaged area. Haemostasis typically occurs within the first few hours after injury and sets the stage for the phase of inflammation. Nevertheless, deficiencies in clotting factors such as VII, IX, or XII can impair this process and delay wound repair.

Inflammatory phase

Tissue injury first triggers the thrombogenesis through platelet activation [37]. The resulting clot, composed of platelets, red and white blood cells, and fibrin fibres, stabilises the wound and acts as a short-term scaffold for incoming cells. Simultaneously, inflammatory mediators such as histamine, prostaglandins, and other amines released from the mast cells cause vasodilation and increase the leakage of capillaries. This allows white blood cells, particularly monocytes, to relocate into the area of the wound, while fluid leakage into surrounding tissues leads to oedema and other typical signs of inflammation, including pain within the next 24-hour period of injury. Neutrophils are the earliest inflammatory cells to reach the wound, guided by chemotactic signals from bacteria, damaged tissues, and activated platelets [37]. Their primary role is to eradicate cellular debris and microbes through phagocytosis, and these cells accumulate with dead tissue, often appearing as pus at the wound site. Bottom of Form

The new tissue formation commences in the proliferative phase following the inflammatory phase. To renovate the lining of epithelium, the keratinocytes from the wound edges will relocate around the wound site, which will be aided by enzymes that break down damaged extracellular matrix. Fibroblasts also migrate into the wound and, together with macrophages, form granulation tissue, while angiogenesis leads to the process of neovascularisation to facilitate the transport of essential nutrients and oxygen for repair. Some of these fibroblasts will eventually develop into myofibroblasts, which help in the contraction of the wound edges. In the later stages, there will be an accumulation of lymphocytes [38], especially T cells, in the wound area. These T-cells will secrete cytokines, which will influence the function of fibroblasts and macrophages [39]. Some T-cells in the skin will help in the maintenance of tissue integrity and the proliferation of keratinocytes [40]. Bottom of Form

Proliferative phase

This phase starts on the second or third day and lasts for three to four weeks. This phase corresponds to the inflammatory phase and is marked by the process of cell migration, cell multiplication, and the formation of new tissues [39]. Fibroblasts start to arrive in the area close to the

wound by the third or fourth day and reach a maximum by the seventh or fourteenth day. These cells migrate to the early fibrin wound. These cells, in the presence of growth factors such as basic fibroblast growth factor (bFGF), platelet-derived growth factor (PDGF), and transforming growth factor- α (TGF- α), start to synthesise the components of the extracellular matrix, such as fibronectin, collagen, glycosaminoglycans, elastin, and proteoglycans. These components form the granulated tissue, which gives the necessary framework for the healing process and cell adhesion. These components also provide the wound with the necessary tensile strength.

During the same time, the process of angiogenesis also begins. This process ensures the supply of essential nutrients and oxygen to the wound area. This process is mediated by the growth factor, vascular endothelial growth factor (VEGF), which is produced by cells such as keratinocytes, macrophages, fibroblasts, and platelets in the wound area in response to hypoxia and the wound's metabolic activity [38]. Endothelial cells grow out from the adjacent intact vessels and migrate to the wound area. These cells later on form new vessels by the process of proteolytic degradation of the wound's extracellular matrix and fibrin network. The newly formed capillary beds, which reestablish blood flow in the developing granulation tissue [39]. With the reestablishment of blood flow, the production of angiogenic factors decreases, and the superfluous blood vessels regress via apoptosis, which contributes to the colour change in the mature scar tissue.

Re-epithelialisation also occurs during the proliferative phase to regenerate the skin's protective surface [41]. Keratinocytes located at the wound margins, activated by growth factors such as epidermal growth factor (EGF) and transforming growth factor- α (TGF- α), begin to multiply and relocate over the wound surface in the initial 12–24 hours after injury. Their movement continues until cells from opposite sides meet, after which migration stops, and stable connections with the newly formed basement membrane are established. Around one week after injury, some fibroblasts differentiate into myofibroblasts, which bring the wound margins closely together and promote wound contraction. This contraction reduces the size of the wound and decreases the amount of extracellular matrix required for repair. Nearing completion of this phase, fibroblasts gradually experience apoptosis, leaving mainly a collagen-composed tissue structure that forms the basis of the developing scar.

Remodelling phase

The final stage is the maturation or remodelling phase, which usually begins around the eighth day after injury, continuing for several months or even up to two years based on the wound's size and severity. During this phase, the collagen matrix is gradually remodelled to improve the stability and strength of the healed tissue. Early type III collagen is gradually replaced by robust type I collagen, while new collagen continues to be produced. Older collagen is simultaneously broken down by collagen-degrading enzymes, maintaining a balance between production and destruction. The new collagen fibres are reorganised, cross-linked, and reoriented along the direction of mechanical stress, although they never achieve the same structural organisation as normal, uninjured skin. Another important feature of this phase is the decline in cellular activity within the wound site. In this phase, a significant number of cells that were active during earlier stages, such as macrophages, fibroblasts, keratinocytes, and myofibroblasts, undergo programmed cell death. At the same time, the blood vessels formed during the earlier proliferative phase are destroyed as they are no longer required. This allows the density of these blood vessels to be returned to near normal levels. The fibroblasts continue to play a role in the remodelling phase by controlling the production and degradation of extracellular matrix components via enzymes, such as matrix metalloproteinases. This results in a decrease in erythema, scar thickness, and an increase in tensile strength of healed tissue. However, the tensile strength is only increased to 80% of normal.

Meanwhile, in the interim period, stem cells have a crucial function in the repair and regeneration of tissues. Epidermal stem cells in the hair follicle bulge and the deepest layer of the epidermis play a major role in the migration of keratinocytes in the regeneration of the skin's

outer layer. Bone marrow-derived stem cells, including hematopoietic stem cells and mesenchymal stem cells, have shown the potential for differentiation into various cell types, including fibroblasts, keratinocytes, and various elements of connective tissue. Furthermore, endothelial progenitor cells from these stem cells are involved in the formation of new blood vessels, especially in hypoxic wound environments. A proper balance between the synthesis and degradation of the extracellular matrix is important in the development of scar tissue. Imbalances in this matrix can cause abnormal scarring, including hypertrophic scarring and keloid formation. In addition, nutritional status can also cause delays in the synthesis of collagen and trigger the risk of delayed healing or wound breakdown. Top of Form

Factors Affecting Wound Healing

Different factors can interfere with the normal healing process of the wound. The factors can be categorised as local factors and systemic factors. The local factors can directly affect the wound site, thereby affecting the surroundings. There are instances where extraneous matter, contamination, lack of sufficient oxygen, etc., can interfere with the healing processes [42].

Systemic factors, on the other hand, are related to the state of well-being of the body. Factors like age, sex, hormonal levels, and psychological stress can affect the healing capacity of the body. Moreover, factors like diabetes, obesity, nutritional deficiencies, and immune status, etc., can interfere with the healing capacity of the body. Lifestyle factors such as lack of exercise, excessive intake of alcohol, smoking, etc., have a major impact on the body's capacity to restore tissue. These factors can affect the healing capacity of the body by affecting the surroundings of the wound. These factors are illustrated in figure 6.

Local factors

Foreign bodies and necrotic tissue interference

The presence of foreign particles and dead tissue [43] in a wound may cause a delay in the healing process since these elements will continue to

promote inflammation and create a suitable condition for infections [44]. These elements will promote microbial growth and prevent the normal repair of tissues. Thus, proper debridement of the wound is important since it removes dead tissues and foreign particles from the site of injury. This will promote a clean wound condition and encourage the healing process to enter the proliferative phase for new tissue formation.

Oxygen

For proper wound healing, the body needs an adequate oxygen supply for the tissues. A brief period of temporary hypoxia right after an injury will accelerate the healing process and stimulate the growth of new blood vessels. On the other hand, long-term oxygen deprivation (prolonged hypoxia) will slow the process by which wounds heal. Oxygen is required for angiogenesis, collagen production, cellular metabolism, and the body's response to infections caused by bacteria [43]. Long-term hypoxia will cause less collagen production from fibroblasts, and therefore, tissue repair will be slowed down.

Moisture balance

A proper moisture level in the wound environment is essential for optimal healing. The presence of excessive dryness can slow the movement of epithelial cells across the wound surface, ultimately slowing down the pace of healing and the process of tissue regeneration. Conversely, excessive amounts of wound exudate will result in softening and damaging the surrounding skin. This condition, referred to as maceration, significantly increases the risk of developing an infection. Due to this, one of the focuses of modern wound treatment is to maintain a balanced moist environment, promoting cell migration and growth [44].

Infection

Infection and high microbial load [43] in the wound bed can delay healing by prolonging the inflammatory phase. Major contributors to the supply of oxygen and nutrients to the wound area are the local vascular supply and blood circulation to the area.

Pathogenic microorganisms compete with surrounding tissue for vital

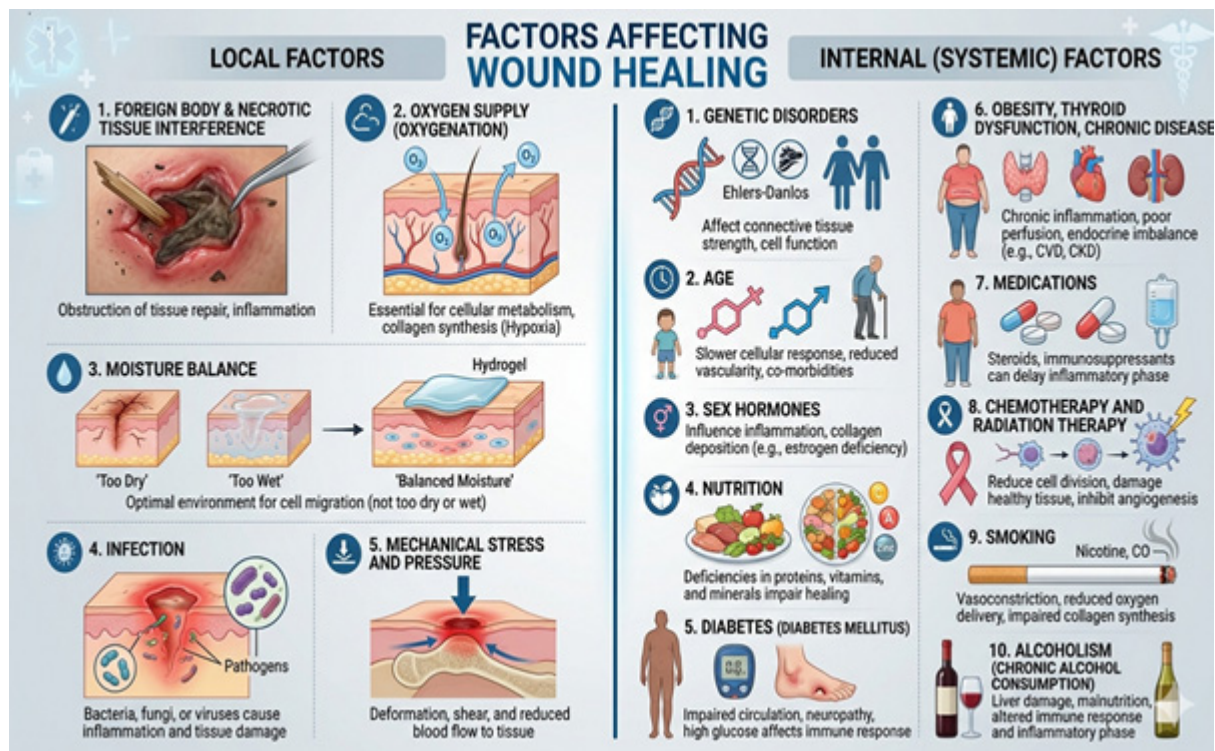


Figure 6: Factors affecting wound healing

sources such as nutrients and oxygen at the wound site and secrete harmful toxins and proteolytic enzymes that damage tissues. Such substances can break down important growth factors needed for repair. Additionally, biofilm formation also safeguards bacteria from host defences and antimicrobial therapies, contributing to delaying healing.

Tissue perfusion

The primary contributors to supplying oxygen and nutrients to the area of wound tissue are blood circulation (and the blood vessels that deliver the blood to the wound) and vascular perfusion, which helps to provide nutrients to the cells responsible for healing [45]. When the blood flow is compromised due to a traumatic wound, swelling, or blood vessel dysfunction, the amount of essential nutrients is greatly reduced. This causes a delay in the creation of new granulation tissue. A reduction in blood supply will result in a reduction in collagen production [45], an important component of mechanical strength, and can lead to a prolonged healing time.

Mechanical stress and pressure

Mechanical stress and continuous pressure may adversely affect the wound healing process [46]. Wounds subjected to continuous trauma or undue tension on the wound site may impede the growth of newly developed tissue. Furthermore, long-term pressure may also restrict blood flow to the area around the wound, reducing the oxygen and other important nutrients being supplied to the tissue for healing. Under these circumstances, there is an increased likelihood that the wound will separate again (dehiscence). Thus, it is essential to relieve pressure and secure the wound to ensure appropriate healing.

The local characteristics of a wound are important factors in determining how quickly and effectively a wound heals; these characteristics directly impact the biological and physical conditions present at the site when tissue repair occurs. Local characteristics refer to all of the elements that interact to create the microenvironment of a wound, such as tissue perfusion, oxygenation, infection, moisture balance, necrotic tissue, inflammation, and mechanical stress. When these factors are present in a positive manner, they will help support the essential healing activities that take place during the wound repair, including cellular migration, angiogenesis, collagen synthesis, and epithelialization. Conversely, when local conditions are negative (i.e., inadequate perfusion, excessive exudate, microbial contamination, or ongoing inflammation), they may disrupt the normal sequence of healing, thereby producing chronic wounds resistant to healing or causing them to occur for a considerable length of time. Therefore, in order to effectively manage a wound, the healthcare provider must not only provide appropriate care to the external surface of the wound and promote healing, but also provide appropriate care to the local characteristics of a wound and, therefore, must modify and improve them. Some of the strategies that can be used to manage local characteristics of a wound include appropriate wound cleansing, prevention of contamination, removal of necrotic tissue, maintenance of an optimal moisture balance, and providing protection from reinjury to the wound. By managing local wound characteristics appropriately, the healthcare provider can increase the effectiveness of wound healing, restore function within the wound bed, and reduce the risk of complications.

Internal factors

Internal or systemic factors markedly affect the wound healing process by affecting the body's ability to regenerate tissue. These factors operate at the level of the whole organism and regulate processes like immune response, cellular activity, blood circulation, and metabolism. Age, nutrition, hormonal balance, and overall health are major determinants in how well the body responds to injury. When systemic conditions are good, they help maintain proper inflammation control, cell growth, collagen production, and tissue regeneration. However, poor conditions like malnutrition, chronic illnesses, diabetes, or weak immunity can slow down healing. These issues may interrupt the normal stages of wound repair. Consequently, wounds may take a longer time to heal and be susceptible to infection. Optimal wound management, therefore, requires

both proper wound care and attention to the patient's overall systemic health.

Genetic disorders

Certain genetic connective tissue disorders can raise a patient's risk of complications during wound healing. These disorders often disrupt the integrity and function of connective tissues, which affects effective tissue regeneration. Genetic factors influence the body's healing mechanisms, including cytokine production, growth factor signalling, and extracellular matrix remodelling. Variations in these genetic processes can result in different responses to tissue injury among individuals. Consequently, some people may experience slower healing or impaired tissue regeneration. Genetic predisposition can increase the chances of chronic wound development and may lead to improper scar formation, including excessive or poor-quality scar tissue. Therefore, genetic background is important in determining individual healing outcomes. AI and computational models analyse genomic and transcriptomic data to identify genes involved in inflammation, collagen production, angiogenesis, and tissue regeneration that affect wound healing. Machine learning can also classify patients by healing risk through the detection of genetic variants linked to chronic wounds and weakened immune responses.

Age

The efficiency of wound healing is significantly influenced by age. With increasing age, several metabolic and systemic changes occur that delay the healing efficiency. The epidermis also tends to become thinner, making the tissue more vulnerable to injury. Inflammatory cell performance is declined by the ageing process, including delayed leukocyte migration and decreased macrophage activity, such as phagocytosis. In addition, there is reduced secretion of cytokines and growth factors, which influences the tissue remodelling. Elderly individuals often experience delayed re-epithelialisation and impaired angiogenesis during healing. Fibroblast activity and collagen synthesis are also reduced, leading to slower wound closure. As a result, healed tissue may have lower tensile strength and overall impaired healing. AI predictive models use age-related biomarkers, including reduced stem cell activity, slower collagen formation, and impaired vascularisation, to estimate wound healing timelines. Computational simulations also assess age-related changes in inflammation and tissue repair to predict delayed healing in elderly patients.

Sex hormones

Sex-related hormones impact wound healing as age increases. In older adults, the rate of wound healing is typically slower in men than in women. Oestrogen improves wound healing in both men and women by reducing inflammation, lowering leukocyte infiltration, and decreasing pro-inflammatory cytokines. It also promotes proliferation and migration of keratinocyte and endothelial cells, leading to improved re-epithelialisation and new blood vessel formation. In contrast, androgens such as testosterone and 5 α -dihydrotestosterone can delay healing by increasing inflammatory cytokines and leukocyte migration [47, 48]. Glucocorticoids further impair wound healing by dampening the inflammation, suppressing fibroblast activity, and reducing collagen synthesis. Overall, oestrogen supports wound healing, while androgens and glucocorticoids tend to inhibit the process [48]. AI models analyse hormone levels such as oestrogen, progesterone, and testosterone to predict their influence on inflammation and tissue repair. Computational studies show that oestrogen can enhance angiogenesis and collagen production, while hormonal imbalances may slow wound healing.

Nutrition

Wound healing necessitates sufficient nutritional support for tissue regeneration. Important nutrients include proteins, carbohydrates, vitamins, minerals, and fatty acids. By regulating the arachidonic acid pathway and supporting cell membrane formation, omega-3 fatty acids contribute to effective wound regeneration [49]. Vitamin A plays a major role in keratinocyte proliferation, which aids skin regeneration [49, 50]. Vitamin C accelerates collagen formation and tissue repair [50]. Carbohydrates are mainly responsible for providing energy and supporting

collagen synthesis. During the healing process, proteins promote tissue growth and repair. Iron plays a vital role in oxygen transport in tissues by preventing hypoxia, and it is a major component of haemoglobin. The body requires enough nutrients from all of the above-mentioned resources in order to heal wounds quickly and effectively. Predictive analytics platforms assess nutritional biomarkers, including albumin, protein intake, vitamins, and micronutrient levels, to estimate wound healing efficiency. Machine learning can link malnutrition with delayed tissue repair and weakened immunity, supporting targeted nutritional interventions.

Diabetes

There is an increased occurrence of complications related to wounds in the diabetic population. It is believed that one of the causes for the heightened frequency of postoperative wound complications in diabetic individuals undergoing surgery is due to the common complications related to surgery and the metabolic imbalance associated with diabetes [51]. Because diabetes has created a large population where individuals have impaired wound healing can be quite significant. These patients may experience complications ranging from minor wounds to severe conditions that can lead to amputation [52]. A diabetic foot ulcer (DFU) is a major setback in patients with diabetes, resulting in approximately 84% of lower limb loss related to diabetes [53]. Additionally, sensory nerves contribute to the regulation of immune defence mechanisms, as skin that has lost nerve supply shows decreased leukocyte infiltration. Individuals with diabetes experience compromised wound healing, which is often impaired due to multiple biological disruptions, such as tissue hypoxia, malfunction of epidermal cells and fibroblasts, decreased new vessel formation, limited neovascularisation, elevated metalloproteases levels, and damage induced by reactive oxygen species (ROS) and advanced glycation end products (AGEs). Diabetes also weakens the immune response and contributes to neuropathy, further impacting healing. Additionally, damage to the skin microvasculature creates a hypoxic environment that limits proper blood supply. The disease impacts the multiplication and differentiation of keratinocytes and fibroblasts, which delays re-epithelialisation and remodelling of the extracellular matrix [54]. AI-driven wound prediction systems analyse blood glucose, HbA1c, neuropathy, and vascular parameters to predict diabetic wound healing outcomes. Computational models also simulate impaired angiogenesis, chronic inflammation, and infection risk to estimate the likelihood of chronic non-healing ulcers.

Overweight, thyroid dysfunction, and other chronic diseases

Excessive body fat raises the chance of developing multiple disorders and health-related complications, including heart disease, hypertension, hyperlipidaemia, stroke, type 2 diabetes, sleep apnoea, respiratory illnesses, cancer, and delayed wound healing. It is considered a chronic medical condition that can impair wound healing. Individuals with obesity often experience chronic wound risks such as pressure ulcers and venous ulcers, often accompanied by swelling, seroma formation, haematoma, and localised contamination. Obesity also triggers a persistent low-level inflammatory response in the body. A deficiency of thyroid hormones can disrupt the normal functioning of multiple body systems, including the cardiovascular, pulmonary, renal, and central nervous systems. It can also modify the way drugs are metabolised, potentially increasing the risk of complications during or after surgery. In addition, research studies have shown that thyroid dysfunction may lead to abnormalities in collagen production, which highly impacts the healing efficacy of individuals.

Insufficient thyroid hormone levels can interfere with the proper functioning of multiple body systems, including the cardiovascular, pulmonary, renal, and central nervous systems. It can also modify the way drugs are metabolised, potentially increasing the risk of complications during or after surgery. In addition, research studies have shown that thyroid dysfunction may lead to abnormalities in collagen production, which contributes significantly to wound healing. Computational modelling integrates comorbidities such as cardiovascular, kidney, and autoimmune diseases to evaluate their impact on wound healing. AI algo-

gorithms identify interactions between inflammation, poor circulation, and immune dysfunction that contribute to delayed wound closure.

Medications

Several medications can hinder the healing process by interfering with the clotting cascade, inflammatory processes, or cell growth. Drugs such as corticosteroids can reduce collagen formation and delay inflammation, while immunosuppressants and chemotherapeutic agents weaken the body's ability to fight infection. Systemic glucocorticoids (GCs), commonly used as anti-inflammatory drugs, may impair the healing process by reducing inflammatory activity and suppressing cellular mechanisms involved in repair, such as fibroblast proliferation and collagen production. Some medications also affect blood flow, oxygen delivery, or nutrient absorption, all of which all support the process of tissue repair. Over time, these effects can impact wound closure by reducing tissue stability, elevating the risk of contamination or the emergence of persistent chronic wounds. Nonsteroidal anti-inflammatory drugs (NSAIDs) can detrimentally impact wound healing by attenuating the inflammatory phase, which is essential for initiating tissue repair. NSAIDs can also reduce platelet aggregation, increasing the risk of blood loss around the wound area. Prolonged or excessive NSAID use may therefore delay tissue regeneration and weaken wound strength, particularly in the early wound healing stages. Machine learning models analyse medication histories to assess how corticosteroids, immunosuppressants, anticoagulants, and antibiotics affect wound repair. Predictive systems estimate delayed healing risks by evaluating drug-related changes in inflammation, collagen synthesis, and immune response.

Chemotherapy and radiation therapy

Chemotherapy medications can impair wound healing, as they often inhibit cellular metabolism and cell proliferation, leading to a delay in key processes such as re-epithelialisation, angiogenesis, collagen production, and wound contraction [55]. Chemotherapy also interferes with collagen production and new blood vessel formation, limiting tissue regeneration. Together, impaired cell proliferation, reduced immunity, and decreased tissue repair capacity result in slower wound closure and a higher likelihood of wound complications. Chemotherapy and radiation therapy are both believed to play a negative role in the wound healing process. Both chemotherapy and radiation can disrupt and prolong the inflammatory phase of healing and may be a factor in decreased fibrin formation, decreased collagen production, and decreased speed of contraction of wounds [56]. Additionally, radiation disrupts the inflammatory response that contributes to decreased regenerative capacity of the skin; therefore, wounds will take longer to heal in tissue that has been irradiated. Irradiated tissues are also at a higher risk of delayed healing, infection, and breakdown when surgery or accidental trauma occurs in an area that has been irradiated. AI systems predict wound healing complications in cancer patients by modelling the effects of chemotherapy and radiation on cell growth, vascular damage, and immunosuppression. Computational simulations also estimate recovery timelines by analysing radiation exposure and treatment-related tissue toxicity.

Smoking

Smoking is also associated with an increased risk of various health-related disorders, including delayed or impaired wound healing. Research has shown that chemicals found in tobacco smoke, such as nicotine, carbon monoxide, and hydrogen cyanide, etc., can have a negative effect on the regular biological processes involved with the repair of wounds. Nicotine causes significant vasoconstriction, which disrupts microcirculation and adversely affects the wound-healing process [57]. Smoking also interferes with the movement of cells and the malfunction of neutrophil function throughout the inflammatory stage. Therefore, smokers have a great risk of wound healing complications compared to non-smokers [58]. Smoking can decrease the activity of macrophages, lymphocytes, and neutrophils, resulting in the weakening of the immune system, thereby increasing the likelihood of infection. Tobacco smoke has been found to negatively affect multiple cell functions and biological mechanisms involved in wound healing [59]. While smoke exposure,

nicotine and carbon monoxide together influence tissue hypoxia. Smoking raises the likelihood of developing several serious health issues, such as cardiovascular diseases, chronic respiratory illnesses, stroke, and cancer. Cigarette-related chemicals can also reduce fibroblast movement, limit their proliferation, and interfere with the remodelling of collagen [60]. Predictive AI models evaluate smoking history, nicotine exposure, and oxygenation levels to estimate the effects of vasoconstriction and hypoxia on wound healing. Computational studies also simulate reduced blood flow and impaired fibroblast activity linked to delayed wound closure.

Alcoholism

Alcohol consumption can disrupt the tissue remodelling phase of healing, reduce collagen production, and modify the levels of extracellular matrix metalloproteinases. Research also indicates that alcohol affects the inflammatory response by an initial suppression of neutrophils and pro-inflammatory cytokines, followed by a rise in cytokine and leukocyte levels in later stages [60]. The greatest negative effect appears to occur in wound angiogenesis, which can decrease by as much as 61% even with a single use of ethanol. Ethanol exposure also impacts the proliferative stage in wound healing during re-epithelialisation, collagen formation, and even wound closure. Evaluation of clinical data suggests that long-term alcohol consumption may result in delayed wound recovery and raised vulnerability to infections. However, the exact biological mechanisms responsible for these effects still require further investigation. The effect of heavy drinking has received an increasing amount of research over the past few years, when compared to how much research has been performed on how smoking affects our bodies, since it is known that there are higher rates of postoperative surgical wound infections among patients who abuse alcohol [61]. Research indicates that the use of heavy drinking will have a direct impact on post-operative infection rates, and acute alcohol intoxication will negatively impact wound healing, combined with the adverse effects of chronic alcohol use [62]. Machine learning models analyse alcohol use, liver function, immune markers, and nutritional deficiencies to predict impaired wound healing. Computational studies show that chronic alcohol consumption disrupts inflammation control and collagen formation, increasing infection risk and delaying wound closure.

To summarise, systemic factors, such as genetic predisposition, advanced age, hormones, nutritional status, dietary habits, diabetes, thyroid diseases, and other chronic diseases, have a substantial impact on the wound healing process. They can change the normal physiological processes involved with tissue repair: inflammatory processes, cellular growth, collagen synthesis, and angiogenesis. Many medications (e.g., chemotherapy and radiation therapy) may affect the activity of damaged cells and cause delays in healing at different stages. Lifestyle choices, such as smoking and drinking too much alcohol, can also negatively affect the healing process by decreasing the amount of oxygen level, undermining the immune response, and disrupting cellular functions. Together, these systemic conditions can slow healing, increasing the risk of infection, resulting in complications like chronic wounds. Therefore, successful wound management requires a comprehensive evaluation of these underlying factors. Healthcare professionals must address both local wound conditions and systemic health issues when planning treatment. Proper management of diseases, balanced nutrition, and lifestyle modifications can significantly improve healing outcomes. Early identification and control of these systemic influences are essential for promoting efficient tissue repair. Considering these factors ultimately helps reduce complications and supports better recovery in patients with wounds.

Wound Dressing and its Importance

In wound management, wound dressings are fundamental, as they develop the conditions necessary for proper wound healing [63]. In clinical practice, a dressing helps the body repair damaged tissue and/or prevents future problems from developing due to infections or slow healing. The proper treatment of all wounds is of utmost importance regardless of whether they are open (i.e., minor cuts) or closed (surgical

incisions) [64]. Placing an appropriate dressing on a wound is one part of providing appropriate treatment to the affected area [65]. The primary purpose of a dressing is to provide a barrier around the wound by placing a wound dressing directly over the actual wound, and the main role of a bandage is to attach the dressing securely to the affected area [64].

Numerous varieties of wound dressings are designed to accommodate the unique features of various wounds. These materials assist in controlling bleeding, promoting clot formation, absorbing excess exudate, and supporting the removal of necrotic tissue during the debridement process. Dressings are therefore developed with the aim of creating optimal conditions that promote efficient wound healing [65]. The prolonged use of dressings for chronic wound care management can impose a considerable economic burden on the healthcare system [65]. However, identifying an ideal dressing material continues to be problematic for healthcare professionals due to the wound's complex nature. Additionally, the rise of multidrug-resistant pathogens and the lack of new antibiotic development have encouraged researchers and clinicians to revisit traditional and alternative therapeutic approaches in wound management [66].

Types of Wound Dressings

Wound dressings are grouped under two main categories: conventional plant-based or conventional dressings and modern multifunctional dressings [64, 65, 67]. Conventional dressings include materials such as cotton gauze, bandages, lint, and plasters. Historically, gauze, lint, plasters, and bandages were made from natural or synthetic fibres or cotton wool [64, 65, 67]. Such conventional materials are typically referred to as passive wound dressings because their principal purpose is to cover the wound and maintain protection and stability. In contrast, modern wound dressings include advanced materials such as foams, films, hydrocolloids, hydrogels, nano scaffolds, and nanoparticle-based dressings [64, 65]. These dressings are considered interactive systems because they actively influence the wound-healing process. Their function involves stabilising the surrounding wound by maintaining appropriate temperature, moisture content, and acidity/alkalinity level. Furthermore, these advanced dressings support the new growth of tissue, assist with the formation of new skin cells, and prevent bacteria from developing or infecting the wound [67]. Both traditional and modern wound dressings are important for healing, but neither type of dressing can replace lost tissue [68]. Human skin substitutes were therefore developed on paper as a replacement for tissue. These substitutes not only enhance tissue repair but also possess the potential to replace damaged or missing tissue [68]. Furthermore, there is evidence from some studies that mesenchymal stem cells derived from the placenta can improve outcomes of the wound-healing process [68].

Traditional wound dressings

Wound dressings, such as gauzes, bandages, plasters, and **lint**, are traditional types of wound dressings that cover either primarily or secondarily the area of the wound to protect that area from contamination [65, 69]. Simple dressings are most often used secondarily to provide a physical barrier over topical medications or primary bioactive dressings.

Gauze dressings can be made from a woven or nonwoven cloth, such as cotton, rayon, or polyester [70]. These materials provide a low level of protection against bacterial contamination since they are mainly a barrier [65]. These sterile absorbent pads made of gauze are often placed on an open wound to absorb exudate or drainage from the wound; however, frequent changings are important to prevent damage to the surrounding healthy tissue from the wet gauze. Although they have become very common for use on wounds, gauze dressings will generally cost more over time because they need to be replaced frequently. If there is a lot of drainage from the wound, the dressing can become overloaded with the fluid and cling to the skin, causing pain and discomfort upon removal [65].

Bandages are used to secure a medical device (either dressings or splints, depending), in order to provide support and/or protection for that body part, by anchoring to the body alone [71]. There are both

natural (e.g., cotton, bamboo, or a blend of cotton/bamboo) and synthetic (e.g., nylon) types of bandages available, each performing different functions [71]. Cotton bandages wound tend to hold dressings in place that are lightweight, whereas the high compression and low-stretch (short-stretch) bandages tend to maintain that pressure for an extended period of time so as to facilitate healing of venous ulcer, specifically. The typical materials for bandaging have traditionally been cotton wadding or cotton, cellulose or other types of polyamide fibres, but with the many developments in advances of the medical textile industry, more current bandages are now being developed with improved performance and new characteristics [72]. In fact, many modern dressings use synthetic polymers. Although there are many different commercial products, including Xeroform™, Bactigras, Jelonet, and Paratulle.

Plaster has been used as a firm support for centuries to treat musculoskeletal injuries (i.e., fractures) that require immobilisation, rest, or structural correction [73]. While many metal implants (internal fixation) have been developed and used in practise over the past 100 years to treat these injuries, plaster, casts, and splints still provide an excellent means for external stabilisation [74]. Medical applications of plaster began with the use of calcium sulphate and were later enhanced with the introduction of crinoline rolls or strips coated with cement-based products that helped make application easier for medical staff [74]. The rigidity of plaster primarily results from the close contact between plaster and the underlying soft tissue. Although plaster provides numerous benefits for patient care, there are limitations associated with its use, including potential complications. Throughout much of the 20th century, plaster was considered the standard treatment for fractures until internal fixation devices became widely adopted in the late 20th century [74]. In addition, plasters provide an excellent alternative method to treat small cuts, scrapes, and other minor wounds because they are easy to apply, so individuals may continue to carry out their usual daily activities with minimal pain or discomfort from applying the plaster.

In ancient Egypt, bandages for wounds were often made up of several different materials, including cotton or linen strips that had been soaked with oils such as grease or honey and placed directly onto the surface of a wound. “Lint” referred to the fibres from plants that were used in the dressing to help absorb [75] blood or other fluids from the wounded body part, as well as provide some protection against bacteria and other sources of infection. In addition to the dressing materials themselves, many times the bandages were soaked in a mixed solution before being applied [76]. These dressings have also been used in modern medicine to provide temporary or supportive cover until the wound has healed completely. Lint-type dressings work well on all areas of your body due to their ability to conform easily to various shape changes or

contours. Some types of conventional are given in figure 7.

Typical conventional dressings are appropriate for both clean wounds with limited exudate and dry ones as a secondary form of protection; nevertheless, due to their non-retentive properties with respect to moisture, they have been slowly replaced by more sophisticated modern dressing formulations. A common challenge in wound care is the stickiness of dressings with the wound surface, leading to both problems in healthcare settings and an extra cost associated with wound care [77]. More sophisticated modern dressing types are more widely used to treat chronic, non-healing, or complex wounds, addressing the constraints of conventional approaches. These advanced dressings come in various formats and designs with improved properties that offer additional functionality over passive bandages, such as antimicrobial effects and moisture regulation to promote healing [78].

Modern wound dressings

The advancement in wound dressing materials over the past few years has been dramatic, with many different options becoming available for practitioners to use based on the unique needs of the patient and their specific type of wound. In addition to providing coverage for the wound, the design of modern dressings has also included mechanisms to facilitate healing, specifically through maintaining moisture within the wound and providing support for tissue regeneration. There are now so many different types of products available that it can be difficult for practitioners to choose which product to use for their patients. Advanced dressings, when categorised by their method of manufacture, fall into three types: passive, interactive, and bioactive. Passive dressings are considered a protectant that does not contain moisture; therefore, they will not promote healing. Interactive dressings are classified as semi-occlusive or occlusive by design, thus reducing the risk of infection while allowing for more effective healing. Finally, bioactive dressings provide an additional active mechanism that helps to stimulate the repair and regeneration of tissue. By classifying various dressings based on their mode of action, it is possible to tailor wound care based on the type of wound and the desired outcome. Types of modern/advanced wound dressings are given in figure 8.

Foam dressings

Foam dressings are becoming more popular and important in managing wounds effectively as a result of the global demand for effective wound care, innovation, and development [79]. Depending on their adherence characteristics, some foam dressings are designed to stay very close to the area of the wound to keep the wound edge moist and prevent it from getting infected, while others are designed to help in reducing skin irritation when removing the dressing from the surrounding skin [79].

Conventional wound dressing



Figure 7: Types of conventional wound dressings

Modern wound dressing



Advanced wound dressing



Figure 8: Types of modern/advanced wound dressings

Furthermore, foam dressings are available with both high and low absorbency and flexibility, making them suitable for use in a wide range of clinical settings. Chronic wounds, including diabetic foot ulcers, pressure ulcers, and venous leg ulcers, are all examples of wounds that have shown an excellent response to treatment with foam dressings [80]. There has been encouraging evidence from clinical studies demonstrating that by combining silver-impregnated foam dressings with vacuum-assisted closure (VAC) therapy, great improvements have occurred regarding the size of the wound and its ability to reduce bacterial growth within the wound [81]. Research studies have shown that using foam dressings as a preventative measure can help reduce the incidence of sacral hospital-acquired pressure injuries in critically ill patients [82]. Foam dressings are typically designed with a protective film packing that helps shield the wound from moisture and microorganisms in the surrounding environment. The film packing has varying permeability, thereby impacting the evaporation of fluids and the exchange of gases [83]. The ability of foam dressings to absorb a large amount of wound exudate regularly results in fewer dressing changes and, therefore, aids in keeping tissue moist for normal healing [84]. The unique physical properties of foam dressings will continue to make their use in chronic wound management useful in maintaining ideal moisture levels for successful tissue healing [85]. There are different types of foam pads; some include other absorbent materials, like viscose or acrylic fibres, and others have superabsorbent polyacrylate to maximise fluid throughput. Some products are coated with silicone to facilitate atraumatic removal with dismounting of the dressing [86].

Despite their benefits, foam dressing materials come with some disadvantages. Typically, sufficient exudate is required for effective use. Therefore, foam dressings are recommended for use on wounds with no/minimal exudate, dry wounds, or dry scar tissue. Common examples of foam dressing products are Lyofoam™, Allevyn™, and Tielle™.

Film dressings

For about two decades, transparent adhesive polymeric film dressings have been used in managing wounds [85]. By providing moisture to the environment of the wound, modern dressings, especially film ones, allow for adequate healing of the tissue [86]. The film is generally biodegradable, bio-adhesive, and a hydrophilic polymer, enabling the films to provide effective drug delivery to wet areas, such as wounds and the buccal cavity [86]. Film dressings are thin, elastic, and transparent polyurethane materials that offer protection from bacterial infiltration of the wound area. They also allow gas exchange with oxygen, while protecting the wound from the environment, and are suitable for wound types that are fragile or that produce minimal exudate [87]. Since the film is clear, the clinician has the benefit of being able to see the wound or catheter insertion site without having to remove the dressing. Often, these dressings may be changed less frequently than traditional gauze and tape dressings [88].

In addition to those dressings, the films are very flexible and elastic, allowing them to conform to diverse body shapes without the need for tape for additional support. Because the dressing is transparent, the condition of the wound can be inspected and evaluated without disrupting the covering. Some film dressings also include enhanced securement features that improve stability and help minimise complications [88]. These dressing materials are most appropriate for shallow wounds with limited exudate and superficial lesions, as well as epithelialising wounds. Some commonly used products include Opsite™, Tegaderm™, and Bioclusive™. Commercial film dressings vary in their vapour permeability, adhesive strength, flexibility, and stretchability.

These film dressings lack absorbent capacity, and accumulated wound fluid may lead to skin maceration; hence, they are unsuitable for moderately to heavily exuding wounds [87]. The adhesive layer of the dressing may also damage newly formed skin or surrounding healthy tissue. For this reason, patients with fragile or atrophic skin, especially older individuals, should minimise the dressing changes or refrain from using film dressings. Transparent film dressings must be changed when they become damp, detached, or visibly contaminated [88].

Hydrocolloid dressings

Hydrocolloid dressings are not only effective in handling chronic wounds like pressure sores and leg ulcers, but they are also equally beneficial for treating acute wounds by helping with debridement, absorbing extra wound fluid, and protecting the wound from infection [89]. Hydrocolloid dressings help manage wound moisture by allowing surplus fluid to be released while preventing the wound from drying out [90]. Their ability to handle fluid varies depending on several factors, including physical and chemical attributes of the gel composition and construction of the dressing [90]. Hydrocolloid dressings are occlusive wound coverings typically made of a hydrocolloid layer integrated with a vapour-transmitting foam or film backing. Once the dressing was applied to the wound, the hydrocolloid material turned into a gel to maintain the moisture needed for effective healing [91]. Hydrocolloid dressings are well recognised for their role in chronic wound care, but evidence regarding their efficacy in acute postoperative wound care in dermatological practice requires further investigation.

In addition to promoting wound healing, these dressings may provide other advantages such as improved patient comfort, greater convenience, perceived enhancement in scar appearance, and easier wound care management, although more research is required to confirm these benefits [92]. Products such as Granuflex™, Comfeel™, and Tegaserb™ are commonly obtainable in sheet-form or thin-film-form dressings. However, there are some constraints in using hydrocolloid dressings; they are not ideal for perforating foot ulcers or wounds with heavy exudate and are frequently employed as secondary dressings.

Hydrogel dressings

Hydrogels are frequently utilised in the management of burn wounds, pressure sores, devitalised tissues, and chronic dry wounds. These dressings are generally non-irritating, compatible with biological tissue, and permit metabolic transport. Recent advancements in wound care have focused on developing “active dressings”, in which hydrogels are integrated with additional components to further support and improve the wound-healing environment [93]. Hydrogel dressings are considered one of the most appealing and effective options for wound management due to their strong moisture-retaining ability, excellent biocompatibility, and beneficial therapeutic effects. With growing awareness of the biological mechanisms contributing to wound formation, recent studies have introduced various functionalised hydrogel dressings that have demonstrated promising outcomes in facilitating the healing of wounds associated with diabetes [94]. Hydrogel differs from other sophisticated dressings, such as hydrocolloids, films, and foams, by its unique degradation characteristics, which permit precise delivery of bioactive substances to the wound area [95]. Hydrogels are also regarded as a highly promising type of temporary dressing for burn injuries. Since they consist of more than 90% water, they help speed up the healing process by maintaining adequate moisture. In addition to burns, these types of dressings can be utilised for other types of skin injuries; these types of dressing contain moisture, which helps to promote healing [96]. Recent advancements in technology have now made available a new class of hydrogels called stimuli-responsive hydrogels. These types of hydrogels are able to regulate themselves and promote tissue regeneration by responding to external stimuli [93]. Hydrogel-based electronic skin (e-skin) sensors that have been engineered to incorporate hydrogels are becoming essential for the continuous and real-time monitoring of wound healing parameters, which include pH, temperature, oxygen concentration, glucose, and inflammatory indicators. Smart hydrogels are able to integrate biocompatible materials with flexible bioelectronics and thus offer an opportunity to develop an AI system that is able to detect infections, poor healing processes, and tissue damage before the appearance of visible symptoms [97]. The use of hydrogels as a platform for the integration of e-skin sensors is ideal due to their ability to mimic the biological environment by being similar in softness, hydration, and other physical characteristics, while also having close contact with the wound [98].

One limitation of the hydrogel dressings is that the accumulation of fluid from the wound can cause the dressing to become saturated, which may result in maceration of surrounding tissues and allow for increased

growth of bacteria. These changes can create an unpleasant odour. Also, because hydrogels are typically designed for low mechanical strength, they generally will not have the same level of durability as conventional dressings; therefore, they generally will not be as easy to use during dressing changes. Some hydrogel dressing formulations include Intrasite™, Nu-Gel™, and Aquaform™. Hydrogel dressing products may be supplied as polymer-based films, impregnated gauze, or as a water-based gel.

Nano-scaffolds

Scaffolds are extremely crucial for tissue repair and regeneration. Within the last 20-year period, there have been extensive research efforts to create scaffold materials for use in tissue engineering [99]. Scaffolds are porous three-dimensional biomaterials to aid in supporting the attachment of cells, and their interaction with biomaterials and the proliferation of cells. During the preceding quadrennium, substantial advances in the fabrication of scaffolds have been attained for a range of biomedical purposes. Among the different types, polymeric scaffolds have attracted significant interest because of their distinguishing features, including a large surface-area-to-volume ratio, substantial porosity featuring fine pore structures, biodegradable nature, and desirable mechanical characteristics. Their excellent biocompatibility, chemical adaptability, and supportive biological traits are well-suited for the implementations of tissue replacement and organ substitution [99]. Polymeric scaffolds support cell adhesion and growth, making them valuable in tissue engineering. They can also protect drugs within the body until the time of release. This protective function helps minimise side effects and prevents fluctuations in drug concentration that may occur with repeated doses of immediate-release medications [100]. Drug-delivery polymer scaffolds have been investigated for the therapeutic interventions of numerous disorders, including the primary type of dementia, tumours, cardiovascular disorders, arthritis, and epilepsy [100].

In bone tissue engineering, nanoscale materials can act as scaffolds that support effective tissue repair. They contribute through mechanical stimulation, controlled release of loaded drugs and biological mediators, and by providing a three-dimensional structure that promotes cell expansion and conversion of bone marrow stem cells into osteocytes [101]. As a growing area of research, tissue regeneration seeks to repair damaged tissues by integrating patient- or donor-derived cells with scaffold biomaterials of high porosity that act as frameworks for new tissue formation [102]. Tissue regeneration is a clinical approach used to restore bone and other tissues, including certain body parts and organs. It has also been applied in skin regeneration, although its implementation in an intricate anatomical structure like the heart remains limited. Various fabrication techniques are used to create scaffolds, including electrostatic spinning, particulate leaching, stepwise assembly, and 3D printing. In addition, natural biodegradable scaffolds have been examined for their potential to support cell expansion and regenerative applications [102].

Nanoparticle-based dressings

Bacterial infections in wounds can significantly slow down the healing process and may even pose serious risks to human health. Therefore, there is an increasing demand for the creation of smart wound dressings that combine diagnostic and antibacterial functionalities [103]. Nanoparticles have been extensively researched due to their advantageous features. Recently, there has been growing interest in the use of smart dressings containing nano-particles to both detect bacteria and provide treatment, facilitating more accurate identification of infection and enhanced control of targeted, on-demand treatment [103]. There are several limitations associated with traditional antimicrobial dressings, which include free antibiotic availability to treat infection. One primary limitation of these traditional dressings is the potential for early release of the drug or unintended activation, which significantly decreases the effectiveness of the treatment [104]. Antimicrobial therapies using responsive nanoparticles have been proposed as a viable alternative to overcome these limitations. “Smart” nanoparticles can be designed to respond to specific environmental signals within the wound, including

acidity/alkalinity, chemical-mediated response, specific mechanical signals (e.g., vibration) and external sensory inputs (i.e., temperature, radiance). The use of these stimuli-responsive nanoparticles in wound dressings may enhance the control of infection and provide greater flexibility in controlling the outcome of an injured individual [104].

Nanotechnology enables new methods to hasten chronic and acute wound healing through enhancing wound healing progress across distinct stages, rather than relying on standard techniques alone to improve wound healing rates [105]. Various nanoscale platforms, such as nanoscaffolds, nanofibers, and other biomaterials, are utilised for dermal delivery of therapeutics to improve overall healing outcomes from wounds when using this method. During the last few years, there has been much interest in utilizing nanoscale particles in the biomedical and pharmaceutical fields [105]. Therefore, significant quantities of these materials are being applied in various medical areas, including dressings for wounds, as carriers for therapeutics, and other areas of healthcare. Many of the currently available nanoparticles (NPs) have been shown to serve as effective means for transporting therapeutic agents (including growth factors and nucleic acids) to assist in the regeneration of tissue and therefore promote the healing of wounds. Especially when the nanoparticles are incorporated into a smart matrix to develop a nanocomposite (NCP), they can act as a basis for the development of next-generation dressings for the treatment of wounds [106].

Biocompatible nanoparticles are capable of delivering and releasing therapeutic agents at an ongoing and continuous rate. This has the potential to be superior to traditional methods of treatment. Nanoparticles loaded with drugs, when applied transdermally, allow for drugs to be applied via localised administration to the dermal layer, resulting in more effective outcomes. The multifunctional features of drug-loaded nanoparticles create a unique ability to use them as a platform for developing novel, innovative products for the treatment of wounds [106].

Bio-artificial skin grafts

Skin loss remains one of the most common, long-standing, and expensive challenges in healthcare. Over the years, considerable attention has been directed toward the tissue engineering of dermal, epidermal, and full-thickness skin substitutes using both natural and synthetic biomaterial-based matrices [107]. Temporary wound dressings help prevent dehydration and reduce the risk of infection. Significant research efforts have been directed toward developing artificial skin substitutes that provide effective wound coverage and protection [108].

The evolution of wound management has progressed significantly from ancient practices to advanced modern therapies. With continuous technological development, both the materials and techniques used for treating acute and chronic wounds have undergone major improvements. Early breakthroughs included the use of skin grafts such as xenografts, allografts, and autografts, which became effective approaches for managing burns and traumatic injuries. Amniotic membranes were also introduced as biological coverings for full-thickness burn wounds and as supportive overlays for meshed autografts [109]. As interest in skin regeneration expanded, cultured epithelial autografts and tissue-engineered grafts emerged as innovative therapeutic options. Later, synthetic skin substitutes fabricated from biodegradable polymers provided better control over structural and functional properties while also supporting faster healing and improved drug delivery [109]. More recently, electrospun polymeric membranes have gained attention as potential skin substitutes, although many of these technologies are still being evaluated in preclinical and in vivo studies.

To minimise the risk of infection during healing, researchers incorporated metallic nanocomposites containing agents such as silver and zinc into polymer-based substitutes. In particular, zinc oxide nanoparticles have shown promising effects in promoting angiogenesis and accelerating wound repair. Future developments in skin substitute technology are expected to transform conventional wound care through the creation of smart, cell-free biomaterials. These advanced matrices may not only act as protective barriers against microbial invasion but also regulate moisture, deliver antimicrobial compounds, stimulate blood vessel formation, reduce scar formation, and attract regenerative cells to the

wound site. Incorporation of nanotechnology may further enhance healing by influencing cellular activities and controlling the expression of biomolecules involved in tissue repair at the genomic and proteomic levels [109].

Several commercially available skin substitutes, including Biobrane®, TransCyte®, EZ Derm®, Permacol®, and Matriderm®, utilise cross-linked or composite collagen-based matrices. Current skin replacement strategies involve approaches such as donor cell treatments before or after transplantation, stem cell therapies, and bioengineered acellular or cellular skin equivalents. Despite these advancements, immune rejection remains a significant limitation of many skin substitutes. The development of induced pluripotent stem cells (iPSCs) has introduced the possibility of stem cell banking, which may help minimise graft rejection and improve the feasibility of autologous grafting. In addition, a growing number of bioengineered skin substitutes are now being applied clinically for skin repair and replacement [110]. However, complete and permanent skin regeneration often requires the combination of multiple treatment methods. Although bioengineered substitutes provide several benefits, an ideal commercially available substitute capable of permanent skin restoration has not yet been achieved. Continued progress in biomaterial development and stem cell technology offers promising opportunities for more advanced and effective skin regeneration therapies in the future [110].

3D Bio-printed skin substitutes

Conventional treatment methods, such as skin grafting, are often associated with increased patient morbidity, while alternatives like acellular grafts face limitations related to poor integration with surrounding tissues. In response to these challenges, 3D bioprinting has emerged as a promising technology that utilises natural and hybrid biopolymers to replicate the extracellular matrix (ECM) and create a supportive environment for cell attachment, proliferation, and tissue development. This approach offers the possibility of producing ready-to-use skin substitutes and also enables direct in situ printing of skin onto wound sites according to the wound's depth and complexity [111]. The increasing lack of suitable skin grafts for patients with severe injuries has highlighted the urgent need for advanced regenerative solutions. Over the past few decades, skin tissue engineering has progressed considerably, particularly in the development of artificial skin substitutes. Among the various fabrication methods explored, 3D bioprinting has shown exceptional potential for generating both single-layered and multilayered skin structures using bioinks combined with skin cells or stem cells [112].

Recent developments in this field have focused on improving printing strategies, optimising bioink formulations, and incorporating living cells into engineered constructs. Studies have also emphasised the importance of printing parameters, as they directly influence the quality of the printed substitute and the survival of embedded cells [112].

Bioengineered skin substitutes have become an important therapeutic option for the treatment of skin damage and wounds. These substitutes can be categorised according to their composition and scaffold materials into cellular or acellular types, as well as natural or synthetic grafts [113]. Depending on the skin layer represented, they may also be classified as epidermal, dermal, or composite substitutes. Commercially available skin substitutes are widely used in clinical practice for wound management and tissue repair. In addition, the selection of appropriate hydrogels plays a critical role in designing cell-loaded skin constructs suitable for bioprinting applications [113]. Bio-printed skin constructs provide several advantages over conventional grafting methods by reducing issues related to limited donor tissue availability and complications arising from donor sites. Their customizable three-dimensional structure supports improved functional and structural recovery of damaged tissue [114]. Furthermore, since these substitutes can be fabricated using a patient's own cells and are designed to imitate the natural architecture of skin, they may lower the risk of immune rejection and improve compatibility with the host tissue [114].

Advancements in 3D bioprinting have significantly improved the management of both chronic wounds and acute skin injuries. Ongoing research is aimed at refining printing techniques, developing advanced bioinks, and creating bioactive dressings that support efficient tissue regeneration [115]. Traditional skin substitutes remain valuable in clinical wound care, while integration with technologies such as nanotechnology, organoids, and microfluidics is accelerating innovation in the field. Emerging methods, including AI-assisted bioprinting, in situ bioprinting, and 4D bioprinting, are further expanding the potential applications of regenerative medicine. Despite these advances, continued research and technological improvement are necessary to overcome current limitations and achieve successful large-scale clinical implementation. Although 3D bioprinting demonstrates strong potential for producing precise, reproducible, and functional artificial tissues and organs, several obstacles still prevent the widespread development of clinically practical and cost-effective skin substitutes [116]. One important limitation is that certain bioinks require additional chemical or ultraviolet crosslinking processes to maintain structural stability, which can increase the complexity of in situ therapeutic procedures. Biomaterial types and

Table 6: Biomaterials and their functional characteristics

Biomaterial / Dressing Type	Typical WVTR (g/m ² /day)	Typical Tensile Strength	Drug-Loading Efficiency	Key Functional Characteristics
Foam Dressings	800–5000	0.1–1 MPa	60–90%	Highly absorbent polyurethane foams maintain moist environments and manage exudate effectively.
Film Dressings	300–2000	10–30 MPa	40–70%	Thin semipermeable polymer films provide bacterial barriers while allowing oxygen and vapour exchange.
Hydrocolloids	300–1500	0.05–0.5 MPa	50–85%	Gel-forming matrices absorb wound exudate and support autolytic debridement.
Hydrogels	500–3000	0.01–0.2 MPa	70–98%	Highly hydrated polymer networks support cell growth, cooling, and controlled drug release.
Nano-scaffolds	1000–4000	1–15 MPa	75–95%	Electrospun nanofibers mimic extracellular matrix architecture and enhance cell adhesion.
Nanoparticle Dressings	500–2500	0.1–5 MPa	80–99%	Nanoparticles improve antimicrobial delivery, sustained release, and bioactive targeting.
Bio-artificial Skin Grafts	1000–3000	0.5–5 MPa	50–85%	Engineered living skin equivalents promote vascularisation and long-term tissue regeneration.
3D Bio-printed Skin Substitutes	1500–3500	0.05–2 MPa	65–90%	Layer-by-layer printed constructs replicate skin architecture with embedded cells and biomolecules.

Table 7: Cross-linking behaviour and biological performance of wound healing biomaterials

Biomaterial System	Crosslinking Density – Critical Role	Swellability Ratio / Water Uptake	Specific Material Properties	Molecular-Level Interaction with Wound Bed
Foam Dressings	Moderate polymer cross-linking in polyurethane matrix	High fluid absorption with moderate swelling	Porous, semi-occlusive, moisture-retentive, gas-permeable	Absorbs exudate through capillary action while maintaining a moist healing environment; supports cytokine balance and reduces maceration by regulating water vapour exchange
Film Dressings	Low to moderate cross-linking in thin polyurethane films	Minimal swelling	Transparent, adhesive, flexible, waterproof, but oxygen-permeable	Forms a protective barrier against microbes; interacts mainly through adhesion to peri-wound skin while allowing oxygen diffusion that supports epithelial cell migration
Hydrocolloids	Moderate cross-linking with gelatin, pectin, or carboxymethylcellulose	Moderate to high swelling upon exudate uptake	Gel-forming, occlusive, self-adhesive	Exudate triggers gel formation, promoting autolytic debridement; maintains an acidic microenvironment that modulates bacterial growth and enhances fibroblast activity
Hydrogels	Tunable cross-link density depending on polymer composition	Very high swelling ratio due to the hydrophilic network	Soft, hydrated, biomimetic, cooling effect	Water-rich network facilitates diffusion of oxygen, nutrients, and bioactive molecules; supports keratinocyte proliferation and ECM remodelling through cell-compatible hydration
Nano-scaffolds	Variable nanoscale cross-linking in electrospun fibres	Moderate swelling depending on fibre composition	High surface area, ECM-mimicking architecture, porous	Mimics extracellular matrix (ECM), enhancing integrin-mediated cell adhesion, fibroblast proliferation, collagen deposition, and angiogenesis
Nanoparticle Dressings	Often embedded within moderately cross-linked matrices	Depends on carrier hydrogel or scaffold	Antimicrobial, drug-delivery capability, responsive release	Nanoparticles interact with bacterial membranes, reactive oxygen species, or cellular receptors; enables controlled release of growth factors, antibiotics, or anti-inflammatory agents
Bio-artificial Skin Grafts	Complex biologically cross-linked collagen or fibrin networks	Physiological swelling similar to native skin	Acellularized, bioactive, ECM-rich	Cellular components secrete cytokines and growth factors; collagen matrix promotes fibroblast attachment, angiogenesis, and re-epithelialization at the molecular signalling level
3D Bio-printed Skin Substitutes	Precisely tunable bioink cross-linking density	Tunable depending on the hydrogel bioink composition	Tunable depending on the hydrogel bioink composition	Replicates native skin microenvironment; bioactive hydrogels support cell-cell signalling, vascularisation, and spatial organisation of keratinocytes and fibroblasts for tissue regeneration

their functional characteristics are given in table 6. Biomaterial systems, their cross-linking behaviour and the biological performance of wound healing are given in the table. 7. Biomaterials with their major advantages, limitations, and their enhanced performance over other dressing materials are given in table 8.

Future Directions in Advanced Wound Care Dressings

The mechanisms involved in the wound healing process are highly complex physiological processes and are vital to human survival [117]. Although numerous studies have investigated the physiological mechanisms involved in the process, there are fewer studies that have addressed the topic of wound healing amongst specific patient groups [117]. There are high expectations that advanced dressings will become increasingly complex and provide more assistance towards achieving tissue regeneration and eliminating any hindrances that may prevent wound healing, including bacterial infection and imbalance in chemical environments [118]. Most contemporary dressings not only function to protect wounds from further harm but can also serve as delivery systems for medicines or cells from donor tissue to improve the healing process while at the same time providing moisture to the affected area. Nevertheless, incorporating biologically and chemically active ingredients into traditional

dressings poses questions over whether these should be considered drugs or medical devices [118].

The application of new intelligent and connected wound monitoring devices holds high promise for achieving effective wound care management [119]. This can contribute to positive patient outcomes through increased efficiency due to optimal resource allocation that will ensure no overuse of personnel or other resources in dealing with patients suffering from chronic or refractory wounds [119]. However, the full benefits will remain unrealised until the existing technological issues have been sorted out [120]. The field of wound care continues to grow rapidly alongside technological advancements. Although autologous tissue reconstruction can help overcome obstacles to healing, enhance the activity of wound-healing factors, provide temporary coverage or stabilisation while awaiting definitive treatment, and improve the overall outcomes of reconstructive interventions [120]. Modern wound care products and techniques thus expand the clinician's toolkit, enabling comprehensive management of all facets of wound healing [120]. Continued research and interdisciplinary collaboration are expected to further refine these technologies, making advanced wound care more accessible and impactful in modern healthcare.

Table 8: Types of biomaterial dressings, their major advantages and limitations to advanced systems, as well as their performance over other given dressings

Dressing / Biomaterial	Major Advantages	Limitations Compared to Advanced Systems	Enhanced Performance Over Other Dressings
Foam Dressings	Excellent exudate absorption, cushioning, thermal insulation, and easy handling	Limited bioactivity and poor regeneration capability	Outperform films and hydrocolloids in highly exuding wounds by preventing maceration more effectively and providing superior fluid management.
Film Dressings	Transparent, flexible, waterproof, allows oxygen exchange	Weak absorption capacity and unsuitable for infected or heavily exuding wounds	Outperform foams and hydrocolloids in superficial wounds because they enable visual wound monitoring without removal and reduce friction injury.
Hydrocolloids	Maintain a moist healing environment, support autolytic debridement, and long wear time	Can trap excessive exudate and may promote anaerobic infection in deep wounds	Outperform traditional gauze and films by accelerating epithelialization and reducing pain through moisture retention.
Hydrogels	High hydration, cooling effect, biocompatibility, controlled drug delivery	Low mechanical strength and poor durability under stress	Outperform hydrocolloids and foams in dry or necrotic wounds because they donate moisture and enhance cell migration and tissue regeneration.
Nano-scaffolds	Mimic extracellular matrix, high surface area, promote cell adhesion and angiogenesis	More expensive and technically complex to fabricate	Outperform conventional hydrogels and foams by providing biomimetic structural support that closely resembles native tissue architecture, improving regeneration rates.
Nanoparticle Dressings	Targeted antimicrobial action, sustained drug release, enhanced penetration	Potential nanoparticle toxicity and regulatory concerns	Outperform standard antimicrobial dressings because nanoparticles provide controlled therapeutic release and stronger antimicrobial efficiency at lower doses.
Bio-artificial Skin Grafts	Contain living cells, stimulate vascularisation, and long-term regeneration	Complex storage, immune compatibility concerns, and expensive production	Outperform all passive dressings because they actively participate in tissue repair, restore biological skin function, and support permanent regeneration rather than temporary coverage.
3D Bio-printed Skin Substitutes	Personalised architecture, precise cell placement, multilayer tissue design	High manufacturing cost and limited large-scale clinical availability	Outperform nano-scaffolds and hydrogels by recreating patient-specific skin structures with integrated cells, improving functional tissue restoration and cosmetic outcomes.

Conclusion

In summary, effective wound management relies on in-depth knowledge of wound classification, which guides the selection of suitable intervention strategies. Tissue restoration remains a critical biological function for sustaining life, requiring a thorough understanding from clinicians to ensure effective treatment and prevent complications. As medical science progresses, wound care continues to evolve with innovations in advanced dressings, therapeutic materials, and monitoring technologies. Modern dressings are no longer limited to simply covering wounds; they increasingly function as active therapeutic platforms capable of delivering antimicrobial agents, growth-promoting substances, or even living cells while maintaining an optimal moist environment for tissue repair. Concurrent with these developments, emerging smart and connected monitoring devices hold promise for improving treatment decisions, enabling more precise and efficient management of complex wounds. Despite these technological advances, formulating a dressing that specifically addresses the key obstacles delaying healing could significantly aid clinicians and patients in better addressing barriers to healing and improving clinical and treatment results. Ongoing research and technological advancements in wound dressings remain essential for improving the effectiveness and performance of wound care treatments.

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