Application of 3D Printed Hydrogels in Wound Dressings

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Abstract. This paper focuses on the application of 3D printed hydrogels in wound dressings, and systematically explains its processing methods, application scenarios and development prospects. In terms of processing technology, extrusion molding has become a common method due to its wide material compatibility and low equipment cost, but it has problems of insufficient precision and low printing efficiency; photocuring is known for its high precision and high-quality surface quality, but the material needs to be modified and the equipment is expensive; bio-ink has attracted much attention because it can simulate human tissue and achieve multifunctionality, but it faces the problems of complex preparation and stability. In terms of application, 3D printed hydrogel dressings can maintain wound moisture and prevent infection for burns and scalds in trauma treatment, and can quickly stop bleeding and promote tissue regeneration for trauma; in the treatment of special disease-related wounds such as ulcers and diabetic wounds, customized design and loading of active ingredients can effectively improve the healing situation; intelligent responsive dressings can also dynamically adjust performance according to changes in the wound microenvironment. Although there are currently challenges such as material optimization and cost control, it has brought new breakthroughs to wound treatment and is expected to become the clinical mainstream in the future.

Keywords: 3D Printing; Hydrogel; Wound Dressing; Processing Method; Intelligent Response.

1. Introduction

In modern medicine, wound healing is a complex physiological process involving the interaction of cells, biomolecules and extracellular matrix. Wound dressings are of great significance in promoting wound healing. Traditional dressings such as gauze can protect wounds and absorb exudate, but they have limitations in creating a microenvironment for cell proliferation and preventing infection. As an emerging manufacturing technology, 3D printing technology manufactures objects by stacking materials layer by layer based on three-dimensional model data. It has the advantages of high customization, ability to manufacture complex structures and precise control of material distribution [1]. In the field of biomedicine, its unique properties bring new opportunities for wound dressing manufacturing. Hydrogel is a hydrophilic polymer network material with good biocompatibility. It can simulate the extracellular matrix and provide a suitable environment for cell activity. The high water content enables it to maintain wound moisture and reduce scar formation. It can also achieve functions such as drug sustained release and intelligent response by adjusting the composition and structure. The combination of 3D printing and hydrogel opens up a new path for the development of wound dressings. 3D printing can customize hydrogel dressings according to the shape, size, and depth of the wound, achieving perfect fit with the wound, reducing the risk of infection and promoting healing [2]. For example, traditional dressings are difficult to adapt to irregular wounds, but 3D printed hydrogel dressings can be precisely customized. In terms of processing technology, 3D printed hydrogel dressings have various methods. Extrusion molding uses a nozzle to extrude materials and stack them layer by layer to build a structure. The equipment is simple and the materials are widely applicable, but the precision is limited; photocuring uses photosensitive resin to quickly solidify under light, and can produce high-precision complex structure dressings; biological ink contains cells, growth factors, etc., which gives the dressing more biological functions and helps wound healing and tissue regeneration [3]. In the application of wound treatment, 3D printed hydrogel dressings have broad prospects. In terms of trauma, it can provide protection and promote healing for burns, scalds, trauma, etc.; for wounds with special diseases such as ulcers and diabetic wounds, traditional dressings are not effective. 3D printed hydrogel dressings can load drugs and growth factors to regulate the microenvironment and promote healing. Intelligent responsive dressings can also automatically adjust their performance according to changes in wound pH, temperature, etc. However, this field is currently facing many challenges. The biocompatibility and safety of materials need to be optimized, the high cost of 3D printing equipment restricts large-scale production and clinical applications, and clinical research is relatively scarce.

2. 3D printing processing methods

2.1. Extrusion molding

Extrusion molding is a common method for 3D printing hydrogels for wound dressing manufacturing. Its principle is similar to squeezing toothpaste. The hydrogel material is placed in a special barrel. Under the rotation of the screw or the push of the piston, the material is extruded from a narrow nozzle and stacked layer by layer according to the preset path to finally construct a three-dimensional structure of the dressing. From the actual operation process, as shown in Figure 1, the screw or piston in the equipment is responsible for pushing the hydrogel material, the nozzle determines the shape and size of the extruded material, and the motion control system accurately controls the movement of the nozzle in the X, Y, and Z axis directions to achieve precise molding of the dressing.

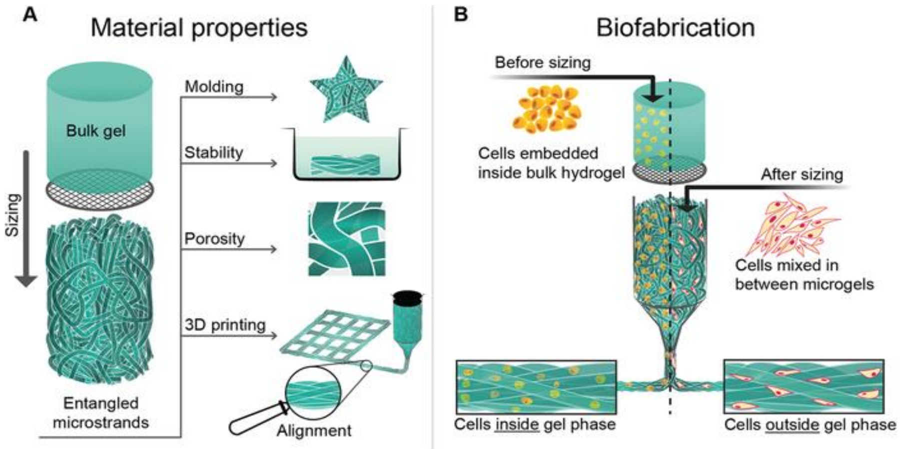

Fig. 1 Extrusion molding 3D printing hydrogel

This printing method has both advantages and limitations. It is compatible with a wide range of hydrogel materials, whether it is natural polymer sodium alginate, gelatin, or synthetic polymer polyethylene glycol, as long as it has a certain fluidity and plasticity, it can be used for extrusion molding. For example, sodium alginate hydrogel, with its good biocompatibility and gelation properties, is often used to prepare dressings that promote wound healing [4]. Moreover, the equipment cost is relatively low and the structure is simple, which is convenient for scientific research institutions and small enterprises to popularize. However, due to the limitations of nozzle size and material extrusion characteristics, its printing accuracy is limited, and it is difficult to produce dressings with fine nano-scale microstructures; at the same time, in order to ensure the stability of material accumulation and molding quality, the extrusion speed is slow, which is not conducive to large-scale rapid production. In the application of wound dressings, there have been many successful cases of extrusion molding 3D printing hydrogel dressings. A research team used this method to produce hydrogel dressings containing chitosan and hyaluronic acid for skin wound treatment. Animal experiments showed that the dressing can effectively accelerate the epithelialization process of wounds, promote healing, and have a mild inflammatory response. However, from the perspective of effectiveness, although its macroscopic structure can fit the wound and provide protection, the deficiencies in its microscopic structure may affect the efficiency of cell infiltration and tissue regeneration [5].

2.2. Photocuring

Photocuring 3D printing technology is based on the photopolymerization reaction of photosensitive resin under the irradiation of light of a specific wavelength to achieve layer-by-layer curing and molding. In the field of hydrogel wound dressing manufacturing, under the action of light, the active groups such as double bonds in the molecules of photosensitive hydrogel materials are cross-linked, and the liquid state is transformed into a solid state to complete the dressing molding. As shown in Figure 2, the photocuring 3D printing equipment is mainly composed of a light source system (such as ultraviolet lamp, laser, etc.), an optical system (to control the shape and direction of the light beam), a resin tank (to hold the photosensitive hydrogel material) and a lifting system (to achieve layer-by-layer printing). Taking digital light processing (DLP) technology as an example, it uses a digital micromirror device (DMD) to pattern the light projected by the light source, quickly cure the photosensitive hydrogel in the resin tank, and stack layers to form a three-dimensional object [6].

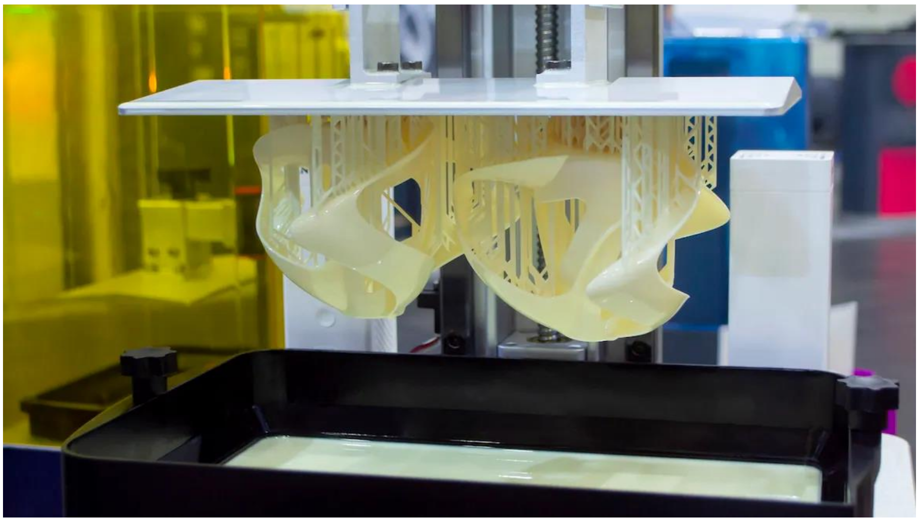

Fig. 2 Photocuring printing equipment

Photocuring technology has outstanding advantages. It can achieve extremely high precision and can produce wound dressings with complex nanoscale pore three-dimensional network structures, which greatly facilitates cell adhesion and growth as well as the exchange of nutrients and metabolic waste. At the same time, the printed dressing has a smooth surface, which can meet the requirements of high surface quality in scenarios such as facial wound dressings. However, this technology also has shortcomings. Not all hydrogels can be used directly and need to be photosensitized, which increases the complexity and cost of material preparation. In addition, equipment using high-precision lasers or advanced optical systems is expensive, which limits its application in resource-limited units.

In practical applications, researchers have used photocuring technology to prepare hydrogel microsphere array dressings loaded with growth factors, which can accurately deliver growth factors to wounds and promote angiogenesis and cell proliferation. The results have been verified by in vitro cell experiments and animal models, and the effect is significant. However, photocuring technology also faces the challenge of limited light penetration depth and difficulty in uniformly curing thicker dressings [7].

2.3. Bio-ink

As a key material for the manufacture of 3D printed hydrogel wound dressings, bio-ink is usually composed of bioactive ingredients such as cells, biomaterials (natural or synthetic polymers), and growth factors. Its uniqueness lies in that it can not only maintain cell activity during the printing process, but also provide a suitable growth environment for cells after printing, helping to achieve tissue engineering wound dressing manufacturing [8].

From the perspective of composition, biomaterials in bio-ink, such as collagen, provide structural support and mechanical properties for dressings with good biocompatibility and cell adhesion; cell components give bio-ink "vitality", and different types of cells can be added as needed to participate in wound repair; growth factors are responsible for regulating cell behavior and promoting tissue regeneration. The wound dressings printed with bio-ink have an orderly and biomimetic structural feature of internal cell distribution.

Bio-ink has the significant advantages of being highly biomimetic and multifunctional. It can simulate the extracellular matrix and physiological environment of human tissue, and can also achieve functions such as drug sustained release and immune regulation by adjusting the formula. However, its preparation process is extremely complex, involving multiple delicate steps such as cell culture and material mixing, and has strict requirements on environmental conditions; at the same time, the cells and bioactive components in the bio-ink are easily affected during storage and printing, and stability assurance has become an important issue that needs to be solved urgently.

In terms of wound dressing applications, the research team used bio-ink containing keratinocytes and growth factors to 3D print skin substitutes for the treatment of large-area skin defects. Preclinical studies have shown that the dressing is well integrated with the wound and promotes skin regeneration. However, bio-ink is still far from large-scale application, and it still needs to overcome difficulties such as cost and standardized preparation.

2.4. Others

In addition to the above common 3D printing processing methods, some technologies are also emerging in the manufacture of hydrogel wound dressings. For example, inkjet printing technology, the principle is similar to that of traditional inkjet printers. Tiny droplets of hydrogel materials are sprayed to the designated position through the nozzle to build the dressing structure layer by layer. This method can deposit materials in small amounts with high precision, which is suitable for the manufacture of dressings with fine patterns or gradient structures, but the fluidity and viscosity requirements of the hydrogel material are almost harsh, and the printing speed is slow.

Selective laser sintering (SLS) technology is also being explored in the manufacture of special hydrogel dressings. It uses a high-energy laser beam to sinter powdered hydrogel materials layer by layer. Although it can produce high-strength dressings with complex internal structures, the high temperature of laser sintering can easily destroy the bioactivity of the hydrogel, and it is currently more in the research and exploration stage. Different 3D printing processing methods have their own strengths in the manufacture of hydrogel wound dressings. With the continuous development and innovation of technology, it is expected that the performance of dressings will be further improved and the functions will be expanded through technological integration in the future, bringing new breakthroughs to wound treatment.

3. Application of hydrogel dressings in wounds

3.1. Trauma field

3.1.1 Burns/scalds

Burns and scalds are common types of trauma. These wounds are prone to infection due to damaged skin barriers, and the healing process is slow. 3D printed hydrogel dressings have become a new choice for burn/scald treatment due to their unique properties. The high water content of hydrogels enables them to simulate the moist environment of human skin, which can not only relieve wound pain, but also prevent wound scabs and promote the migration and proliferation of epidermal cells [9]. For example, 3D printed hydrogel dressings based on sodium alginate, prepared by extrusion molding technology, can fit tightly to irregular burn wounds (as shown in Figure 3). Its internal porous structure provides an ideal scaffold for tissue repair and can also load antibacterial drugs to effectively prevent infection [10].

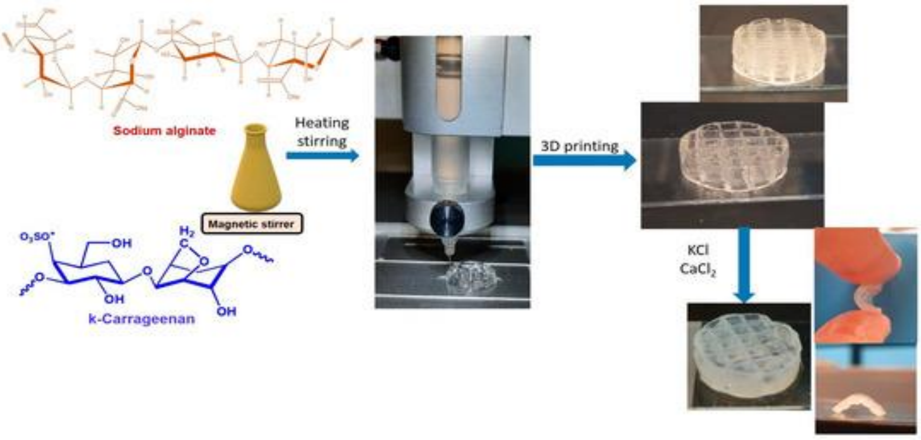

Fig. 3 3D printed hydrogel dressing of sodium alginate

Clinical studies have shown that the wound healing time of burn patients using 3D printed hydrogel dressings is about 30% shorter than that of traditional dressings. From the perspective of mechanism of action, the hydrophilic polymer network in the hydrogel can lock in moisture, reduce the evaporation of moisture from the wound, and maintain cell activity; at the same time, its good biocompatibility reduces the risk of immune rejection. In addition, by adjusting the formula and printing parameters of the hydrogel, dressings of different thicknesses and mechanical properties can be customized to meet the treatment needs of burn wounds of different depths.

3.1.2 Trauma

For traumatic wounds, 3D printed hydrogel dressings also show significant advantages. In the treatment of open wounds caused by accidents or surgery, dressings not only need to have good hemostatic properties, but also need to promote tissue regeneration. Hydrogel dressings containing chitosan perform well in this regard. Chitosan has a natural hemostatic function that can accelerate platelet aggregation and activate coagulation factors to promote rapid hemostasis of wounds. Through 3D printing technology, chitosan hydrogel can be prepared into a dressing with a specific pore structure, which is conducive to cell adhesion and growth, while providing support for new tissue [11]. Animal experiments have shown that in the wound model using 3D printed chitosan hydrogel dressings, obvious granulation tissue formation can be observed two weeks after injury, while the healing speed of the control group using traditional gauze is significantly delayed. In addition, hydrogel dressings can also be combined with growth factors to further enhance their healing effect. For example, loading epidermal growth factor (EGF) into hydrogel can stimulate the proliferation and differentiation of epithelial cells, accelerate wound healing, and reduce scar formation.

3.2. Wounds related to special diseases

3.2.1 Ulcers Ulcers are a common chronic wound, including pressure sores, venous ulcers, and arterial ulcers

The treatment process is often long and complicated. Traditional dressings are difficult to solve the problems of local hypoxia and persistent inflammatory response in ulcer wounds, while 3D printed hydrogel dressings provide a new idea for ulcer treatment. For patients with pressure ulcers, light-cured hydrogel dressings based on gelatin-methacryloyl ester (GelMA) have good elasticity and plasticity, can fit closely to the skin of the body's pressure-bearing parts, disperse pressure, and reduce local tissue damage. At the same time, GelMA hydrogel can load anti-inflammatory drugs, such as dexamethasone, to reduce wound inflammation through sustained release and promote healing [12].

Clinical data show that in cases of venous ulcers treated with 3D printed hydrogel dressings loaded with anti-inflammatory drugs, more than 70% of patients had an ulcer area reduction of more than 50% after 8 weeks of treatment. The advantage of this dressing is that it can be customized according to the shape and depth of the patient's ulcer site, ensuring that the dressing is in full contact with the wound and improving the treatment effect [13].

3.2.2 Diabetic wounds

Due to vascular lesions and nerve damage caused by long-term hyperglycemia, diabetic patients have a significantly reduced wound healing ability. Diabetic foot ulcers are one of the common complications of diabetes and are extremely difficult to treat. 3D printed hydrogel dressings show unique potential in the treatment of diabetic wounds. On the one hand, hydrogels can regulate the humidity of the wound microenvironment, prevent wound drying and scabbing, and prevent bacterial infection; on the other hand, by introducing nanoparticles or bioactive substances into hydrogels, the angiogenesis and antibacterial properties of the dressing can be enhanced [14].

For example, nanosilver particles are combined with hydrogels to prepare 3D printed dressings with antibacterial functions. Nanosilver can release silver ions, destroy bacterial cell membranes, and effectively inhibit the growth of common pathogens such as Staphylococcus aureus and Escherichia coli. At the same time, adding vascular endothelial growth factor (VEGF) to the hydrogel can promote angiogenesis at the wound site, improve local blood circulation, and provide necessary nutrients for tissue repair. Clinical studies have shown that patients with diabetic foot ulcers who use this composite hydrogel dressing have significantly improved wound healing rates and significantly reduced the risk of amputation [15].

3.3. Intelligent responsive hydrogel dressings

Intelligent responsive hydrogel dressings can automatically adjust their own performance according to changes in the wound microenvironment (such as pH, temperature, humidity, etc.) to achieve more precise treatment. Among them, pH-responsive hydrogel dressings have attracted much attention in wound treatment. During the wound healing process, the pH value of its microenvironment will change dynamically, gradually changing from an acidic environment in the inflammatory period to a weakly alkaline environment in the healing period. Researchers have developed pH-responsive hydrogel dressings. When in an acidic inflammatory environment, the acid-sensitive groups in the hydrogel will dissociate, prompting the dressing to release anti-inflammatory drugs; when the wound enters the healing period, the pH value increases, and the hydrogel begins to release pro-healing factors, such as fibroblast growth factor (FGF), to accelerate tissue repair.

Temperature-responsive hydrogel dressings use the thermosensitive properties of hydrogels to undergo a phase transition under body temperature, from liquid to solid, to better fit the wound. This dressing is particularly suitable for burns, scalds, and other situations where the wound surface needs to be quickly covered. For example, poly N-isopropylacrylamide (PNIPAAm)-based thermosensitive hydrogel is liquid at temperatures below 32°C, making it easy to apply or inject into the wound. When the temperature rises to body temperature (37°C), it quickly gels to form a three-dimensional network structure with a certain strength, which protects the wound and promotes healing.

4. Conclusion

3D printed hydrogel dressings integrate the customization advantages of 3D printing technology with the biological properties of hydrogels, opening up an innovative path for wound treatment. At the processing method level, extrusion molding, photocuring and other technologies have their own advantages and disadvantages. With the iteration of technology, it is expected to achieve complementary advantages and improve the accuracy and efficiency of dressing manufacturing in the future. In the application scenario, whether it is common trauma or special disease wounds, 3D printed hydrogel dressings show therapeutic effects that traditional dressings cannot match, especially smart responsive dressings, which make wound treatment more accurate and intelligent. However, the current field is still constrained by problems such as insufficient material biosafety verification, lack of large-scale production standardization, and high equipment costs. In the future, multidisciplinary collaborative innovations such as materials science, biomedicine, and engineering technology will be needed to conduct in-depth research on material properties and cell-material interactions, optimize bio-ink formulations, improve printing processes, and reduce costs. It is believed that through continuous exploration, 3D printed hydrogel dressings will be widely used in clinical practice, providing patients with more efficient and personalized wound treatment solutions.

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