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Research Progress on the Application of 3D-Printed Bioscaffolds in the Repair of Maxillofacial Soft Tissue Defects

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Abstract: Maxillofacial soft tissue defects are common clinical conditions that significantly affect patients' function and appearance. Traditional repair methods, such as autotransplantation and allotransplantation, have achieved certain effects in some cases but still face numerous issues, including donor site injury, limited donor resources, and immune rejection. In recent years, the rapid development of three-dimensional printing (3D printing) technology has provided new ideas and possibilities for the repair of maxillofacial soft tissue defects. This paper reviews the latest research progress of 3D-printed bioscaffolds in this field, focusing on the analysis of key factors such as scaffold material selection, structural design, and biocompatibility evaluation. Meanwhile, the paper discusses the performance of 3D-printed bioscaffolds in preclinical research and practical clinical applications, demonstrating their potential advantages such as personalized customization and promotion of tissue regeneration. However, the current technology still faces challenges, including the long-term stability and functionality of scaffolds. In summary, this paper aims to provide a comprehensive understanding of the application of 3D-printed bioscaffolds in the repair of maxillofacial soft tissue defects and prospect their future development directions.

Keywords: 3D printing, bioscaffold, maxillofacial region, soft tissue defect, tissue engineering.

1. Introduction

The repair of maxillofacial soft tissue defects is a key research focus in the medical field. Trauma, tumor resection, or congenital malformations can severely affect patients' appearance and function. Although traditional autologous tissue transplantation can partially solve the problem, it has limitations such as donor site injury and volume contraction, thus creating an urgent need for new repair methods. In recent years, 3D-printed bioscaffolds have attracted widespread attention due to their advantages in customization—they can accurately match the shape of defect sites and promote tissue regeneration—and their application in the biomedical field has been continuously expanded, especially in tissue engineering. For example, a study developed a multi-component hydrogel scaffold containing gelatin methacryloyl (GelMA), sodium alginate (SA), and bioactive glass microspheres (BGM); this scaffold not only has good biocompatibility but also effectively promotes bone regeneration and soft tissue repair [1], providing a new direction for maxillofacial soft tissue defect repair. In addition, decellularized extracellular matrix (DECM), as a natural biomaterial,

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shows good application potential in tissue engineering—it can promote tissue regeneration and healing through its excellent biocompatibility and structural characteristics [2]. However, the fast degradation rate and insufficient mechanical properties of DECM limit its clinical application, making the optimization of its performance a current research hotspot. Researchers are also exploring the combination of vascularization and soft tissue regeneration: by using intelligently vascularized 3D-printed scaffolds, effective supply of nutrients and oxygen can be achieved to promote tissue regeneration and healing [3], laying a foundation for personalized medicine. In summary, 3D-printed bioscaffolds have broad prospects in this field; with technological progress and biomaterial innovation, safer, more effective, and personalized repair solutions are expected in the future. Nevertheless, clinical translation still faces challenges such as the biocompatibility of materials, the mechanical properties of scaffolds, and their long-term in vivo effects, which should be the focus of future research to promote the application of 3D-printed bioscaffolds in maxillofacial soft tissue defect repair.

2. Clinical characteristics and repair requirements of maxillofacial soft tissue defects

2.1. Anatomical characteristics of maxillofacial soft tissue defects

Maxillofacial soft tissue defects have complex three-dimensional structures, which are closely related to their unique anatomical features. The maxillofacial region involves not only the skin but also the coordinated function of multiple tissue types, such as muscles, fat, and neurovascular structures [4]. This three-dimensional structure makes soft tissue repair more complex, requiring comprehensive consideration of the tissue relationships and functional requirements of each layer. In addition, maxillofacial soft tissue defects affect not only functions such as chewing and speech but also appearance; therefore, both function and aesthetics must be taken into account during the repair process [5,6].

Anatomically, the complexity of maxillofacial soft tissue lies in the organizational structure and function of different layers. For example, the skin covers the underlying fat and muscle layers, while neurovascular structures are distributed between these layers. Such a structural relationship means that any injury may cause significant functional and aesthetic impacts. When repairing these defects, appropriate materials and technologies must be used to ensure that the repaired tissue can restore its original function and shape.

2.2. Limitations of existing repair methods

Current repair methods for maxillofacial soft tissue defects mainly include autotransplantation, allotransplantation, and the use of artificial materials, but each method has significant limitations. Although autotransplantation has good biocompatibility, it often leads to volume loss and complications at the donor site due to the need for tissue harvesting [7]. Allotransplantation can solve the problem of donor site injury, but the risk of immune rejection limits its application. Furthermore, when artificial materials are used for repair, they often face the problem of mismatched mechanical properties, which may result in the repaired tissue failing to meet the patient's functional and structural needs [8].

For instance, when free flaps or other soft tissue flaps are used for repair, postoperative functional insufficiency or poor aesthetics may occur. Although autologous fat transplantation can improve facial contour, it carries risks of fat absorption and uneven regeneration during the transplantation

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process [9]. The limitations of these existing repair methods have driven the medical community to urgently seek new and effective repair materials and technologies.

2.3. Performance requirements for ideal repair materials

Ideal soft tissue repair materials should have multiple properties to adapt to the special needs of maxillofacial soft tissue defects. First, biocompatibility is the most basic requirement: the material must integrate well with human tissues without causing immune reactions or rejection [10]. Second, structural stability is also critical: the material should have sufficient mechanical strength to support the growth and functional recovery of surrounding tissues. The ability to promote tissue regeneration is an important property of ideal materials, which usually requires the material to facilitate cell proliferation and differentiation, thereby accelerating the healing of defect sites [11].

In addition, the processability of the material is an indispensable factor. Ideal repair materials should be customizable according to the specific conditions of the defect to achieve better adaptability and functional recovery. With the development of 3D printing technology, customized bioscaffold materials have provided new possibilities for maxillofacial soft tissue repair. These scaffolds not only provide structural support but also can promote tissue regeneration through drug release, showing good application prospects [12]. By continuously exploring new materials and technologies, future soft tissue repair is expected to achieve better functional and aesthetic outcomes.

3. Material selection of 3D-printed bioscaffolds

3.1. Natural polymer materials

Natural polymer materials play an important role in the application of 3D-printed bioscaffolds, among which collagen and hyaluronic acid are particularly prominent. Collagen is the most abundant natural protein, widely present in the connective tissues of animals; its excellent biocompatibility and biodegradability make it an ideal bioscaffold material. Studies have shown that using collagen as a bioscaffold can promote cell adhesion, proliferation, and differentiation, thereby accelerating tissue regeneration [13]. Hyaluronic acid, an important component of the extracellular matrix, has good moisturizing properties and biocompatibility. It can promote cell migration and angiogenesis, further enhancing the bioactivity and regenerative capacity of the scaffold [14]. In some studies, the combined use of hyaluronic acid and collagen can significantly improve the mechanical properties and biological adaptability of the scaffold, further enhancing its application potential in soft tissue repair [15].

Decellularized Matrix (DECM) materials are another type of natural polymer material that has received extensive attention in the bioscaffold field in recent years. By removing cellular components while retaining the structure and function of the extracellular matrix, DECM materials can provide a natural biological environment to promote cell growth and regeneration [16]. This type of material not only retains the bioactive components of the original tissue but also reduces the risk of immune rejection, thus showing good application prospects in tissue engineering and regenerative medicine. For example, studies have shown that decellularized liver matrix exhibits advantages in promoting hepatocyte function and survival [17]. However, the complex processing process and high cost of DECM materials limit their promotion in large-scale clinical applications.

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3.2. Synthetic polymer materials

Synthetic polymer materials such as polylactic acid (PLA) and polycaprolactone (PCL) also play important roles in 3D-printed bioscaffolds. PLA is a material with good biocompatibility and biodegradability, widely used in medical devices and tissue engineering. It has high mechanical strength, making it suitable for load-bearing scaffold applications, but its brittleness limits its applicability in some cases [18]. In contrast, PCL has good flexibility and ductility, which can effectively improve the toughness and impact resistance of the scaffold, enhancing the scaffold's performance in dynamic biological environments [15]. Studies have found that PLA/PCL composite materials can not only retain the excellent mechanical properties of PLA but also optimize the overall performance of the scaffold by adjusting the proportion of PCL.

In the design of bioscaffolds, balancing the degradability and mechanical strength of the material is an important consideration. The combination of PLA and PCL can achieve performance optimization: PLA provides good strength, while PCL enhances toughness and ductility. Therefore, PLA/PCL composite materials show good prospects in biomedical applications, especially in load-bearing applications [19]. However, as the proportion of PLA and PCL changes, the degradation rate and strength characteristics of the material also change, requiring precise proportion design in practical applications.

3.3. Design of composite materials

The design of composite materials shows significant advantages in improving the performance of bioscaffolds. Combining natural polymer materials with synthetic materials can take full advantage of both. For example, combining collagen with PLA or PCL can improve the biocompatibility of the scaffold while maintaining sufficient mechanical strength and degradability [20]. This composite strategy can not only improve the biological properties of the scaffold but also enhance its mechanical properties, making it more suitable for the regeneration of soft tissue and bone tissue.

In addition, the introduction of nanomaterials can further improve the performance of composite materials. Due to their large specific surface area and unique physicochemical properties, nanomaterials can significantly enhance the mechanical properties and functional characteristics of composite materials. For example, adding nanoscale carbon materials to PLA/PCL composite materials can effectively improve strength and toughness while optimizing biocompatibility and degradation rate. Therefore, combining nanomaterials with traditional bio-based materials can provide new ideas and directions for the design of 3D-printed bioscaffolds.

4. Structural design of 3D-printed bioscaffolds

4.1. Macrostructural design

In the macrostructural design of 3D-printed bioscaffolds, personalized modeling is crucial. Through imaging technology, clinicians can fabricate matching bioscaffolds based on the patient's specific anatomical structure and defect conditions. This personalized approach not only improves the adaptability of the scaffold but also helps enhance its functionality. For example, using solvent-based extrusion (SBE) 3D printing technology, cells can be directly integrated into the scaffold during the printing process, thereby better simulating the characteristics of natural tissue [13]. In addition, the relationship between porosity and mechanical properties cannot be ignored. Studies have shown that appropriate porosity can enhance the mechanical properties of the scaffold while

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promoting the penetration of nutrients and cells, which in turn contributes to tissue regeneration. For example, adding biodegradable suture fibers to reinforced gelatin biomaterials can improve printing accuracy and the mechanical strength of the scaffold, ultimately enhancing the effect of tissue engineering [21].

4.2. Microstructural regulation

In terms of microstructural regulation, the impact of fiber diameter on cell behavior deserves attention. Studies have shown that fiber diameter can significantly affect cell adhesion, proliferation, and differentiation. For example, in 3D-printed bioscaffolds, smaller fiber diameters can provide a larger surface area, thereby promoting cell attachment and growth—this is crucial for tissue engineering [22]. In addition, gradient porosity structure design is also an effective microregulation strategy. By designing scaffolds with different porosities, biological functions in different regions can be realized, providing a suitable microenvironment for cells. For example, studies have found that bioscaffolds with different pore structures can effectively regulate cell behavior and promote bone tissue regeneration [23].

4.3. Surface modification strategies

Surface modification strategies play an important role in enhancing the biocompatibility and functionality of bioscaffolds. Loading bioactive molecules is one effective method. By loading bioactive molecules (e.g., growth factors) on the scaffold surface, the proliferation and differentiation capabilities of cells can be significantly improved. For example, studies have shown that 3D-printed scaffolds loaded with growth factors can promote the proliferation of human fibroblasts and effectively support soft tissue regeneration [15]. In addition, the regulation of micro-nano topological structures has also been proven to be an effective strategy to enhance the biological functions of scaffolds. By adjusting the surface microstructure, cell attachment and proliferation can be enhanced, thereby promoting the effect of tissue regeneration [24]. These surface modification strategies have important application prospects in the design of 3D-printed bioscaffolds.

5. Conclusion

As a notable advancement in biomedical engineering, 3D-printed bioscaffolds provide a personalized approach for maxillofacial soft tissue defect repair, addressing the drawbacks of traditional repair methods. Guided by the clinical needs of maxillofacial soft tissue—including its complex anatomical structure, dual requirements for function and aesthetics, and the limitations of existing repair techniques—research in this field has progressed in key areas: material selection has focused on balancing biocompatibility, mechanical performance, and degradability through natural polymers, synthetic polymers, and composite strategies; structural design has enhanced scaffold adaptability to the natural tissue microenvironment via personalized macro-modeling, refined micro-regulation, and surface modification. While challenges like optimizing material mechanical properties and degradation rates, and advancing multi-material printing for heterogeneous defects remain, ongoing interdisciplinary collaboration will drive 3D-printed bioscaffolds toward wider clinical use, reshaping maxillofacial soft tissue repair and offering insights for tissue engineering.

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