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Optimizing Titanium Mesh Fabrication For Guided Bone Regeneration Via 3D Printing

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***Abstract**:*
The optimization of titanium mesh fabrication for Guided Bone Regeneration (GBR) via 3D printing represents a significant advancement in tissue engineering, offering personalized and highly effective solutions for bone defect repair. Titanium, due to its excellent mechanical properties, biocompatibility, and corrosion resistance, is widely used in GBR applications. This paper explores the potential of 3D printing technologies to create patient-specific titanium mesh scaffolds with optimized structural and biological properties. By manipulating parameters such as porosity, surface texture, and lattice design, it is possible to enhance cell infiltration, promote osteogenesis, and provide mechanical support for bone regeneration. Furthermore, the study addresses challenges in mesh design, mechanical strength, and long-term biocompatibility, while evaluating post-processing techniques and regulatory compliance for clinical implementation. Ultimately, this paper aims to provide an integrated approach to improving the efficacy of GBR, enabling customized titanium mesh implants that enhance healing outcomes.

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I. Introduction

Bone resorption in the alveolar ridge, which begins as early as six months after tooth loss or extraction, can present important challenges for successful implant placement.[1,2] This early and irreversible bone loss can compromise the volume needed for effective implant placement and potentially impact the long-term success of the implants.As a result, restoring the resorbed alveolar ridges has become an essential aim for clinicians focused on improving the outcomes of oral implant procedures[2-4]

To enhance alveolar bone volume, a range of surgical methods have been proposed, including ridge splitting, distraction osteogenesis (DO), and the application of onlay or particulate bone grafts, with or without membranes.[5-8] Autogenous bone, sourced from both extraoral and intraoral donor sites, is commonly used because of its beneficial properties, such as promoting bone growth (osseogenesis), supporting bone integration (osseoconduction), and stimulating bone formation (osseoinduction).[9]

Guided Bone Regeneration (GBR) is a widely recognized technique that delivers reliable results for augmenting bone defects. [10]It operates on the principles of Guided Tissue Regeneration (GTR) by using a barrier to prevent the invasion of fast growing epithelial and connective tissue cells into the bone graft area[11,12]. This allows the slower-moving bone-forming cells to proliferate and develop, thereby creating sufficient bone at the treated site. GBR has become a preferred method for both vertical and horizontal alveolar ridge augmentation, offering the necessary support for osseointegrated dental implants.[13] Moreover, GBR is also effective for regenerating various other types of bone defects.[14]

For Guided Bone Regeneration (GBR) to be successful, it is crucial to maintain space within the bone defect. Soft tissue grows more quickly than bone cells and blood vessels, so a barrier is necessary to stop epithelial cells and connective tissue fibroblasts from migrating into the graft area. This ensures that the slower-growing bone cells have the opportunity to proliferate and mature. This approach is based on the principles of Guided Tissue Regeneration (GTR) used in periodontal regeneration.[15]

Three-dimensional printing, or additive manufacturing[16], is an advanced technology that creates customized 3D objects from computer-aided design (CAD) digital models using standardized materials and automated processes.[17-19] For nearly 30 years, it has been extensively used for rapid prototyping in industries such as design, engineering, and manufacturing. With ongoing advancements in materials, printing technologies, and machinery, 3D printing is set to transform conventional education and experimental practices.[20]

II. Characteristics Of Titanium Mesh

Titanium is favored in surgical applications because of its firmness, low density, noncompliance to corrosion, and excellent biologically acceptable. Titanium mesh, a product derived from this material, offers unique qualities that make it an effective barrier membrane for Guided Bone Regeneration (GBR) in bone augmentation procedures.[21]

Mechanical Characteristics

Titanium mesh boasts remarkable mechanical characteristics , including dense and firm, which offer robust support for bone formation. Its firmness is essential for preserving the volume of bone grafts during the healing period, and its elasticity helps alleviate pressure on the oral mucosa. [22]The mesh's excellent plasticity allows it to be shaped and bent to fit different bone defects. These characteristics enable titanium mesh to provide a stable osteogenic outcome and support simultaneous bone augmentation in both horizontal and vertical dimensions.[23]

Biological properties and osteogenic property

Titanium mesh demonstrates excellent biocompatibility, allowing it to integrate seamlessly with tissues. This biocompatibility is attributed to its resistance to corrosion and low cytotoxicity. Due to its low electrical conductivity, titanium undergoes electrochemical oxidation to form a stable, inert oxide layer, which remains intact in the body's pH environment.[24] This oxide layer ensures high and persistent corrosion resistance, resulting in minimal release of metal particles from the mesh, which do not significantly impact the growth rate of human cells. [25,26]

III. 3D Printing

3D printers operate in a manner similar to traditional laser or inkjet printers, but instead of using multicolored inks, they utilize powder or liquid resin, which is gradually built up layer by layer based on a digital image. These printers rely on 3D CAD software to analyze thousands of cross-sections of the object to decide the precise construction of each layer. The printer deposits a thin layer of liquid resin and employs a computer-controlled ultraviolet laser to harden each layer according to the specified cross-sectional pattern. Once the printing is complete, any excess soft resin is removed using a chemical bath.[27]

Various Technologies Used in 3D Printing [28]

While the fundamental technology behind 3D printers is the same an automated, additive manufacturing process, various principles guide the operation of different types of 3D printers.

The technologies under consideration here are as follows:
Stereolithography (SLA)
Direct Light Processing (DLP)
Fused Deposition Modeling (FDM)
Inkjet Powder Printing
Selective Laser Sintering(SLS)/Direct Metal Laser Sintering (DMLS)

Advantages And Disadvantages Of 3D Printing [29]

Advantages of 3D Printing:

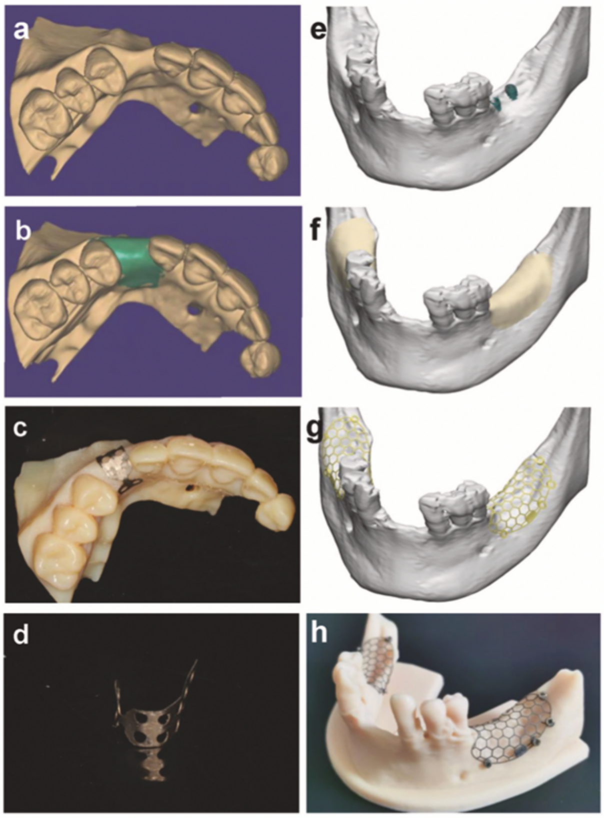
- **Time Efficiency:** Rapid production and reduced manufacturing time.
- **Precision:** Detailed and accurate reproduction of scans, resulting in high-quality and dependable outcomes.
- **Complexity:** Ability to print intricate geometric shapes and interlocking parts without the need for assembly.
- **Material Efficiency:** Minimizes waste associated with traditional manufacturing processes.
- **Flexibility:** Enables the production of single items in small quantities for fast delivery.

Disadvantages of 3D Printing:

- **Material Costs and Availability:** The cost and availability of materials can be a limitation.
- **Training Requirements:** Requires specialized training for effective operation.
- **Post-Processing:** Finishing the final product can be time-consuming and demands skill.
- **Part Quality:** The layer-by-layer deposition process can result in inherent weaknesses in the final part, impacting overall quality.
- **Strength:** Some materials may need additional treatment to achieve full strength.

3D Technology, bone defect dimension and GBR:

The use of 3D technology and additive manufacturing has enabled the creation of customized grids for Guided Bone Regeneration (GBR) tailored to bone deformities, incorporating optimal physical and biological properties. Unlike standard titanium meshes, the smooth edges of 3D-printed titanium mesh help reduce common complications such as mucosal rupture and mesh exposure. This technology allows for more precise construction to match the bone irregularities of the surgical site.[30,31] The effectiveness of bone augmentation with 3D precision is not considerably affected by the size of the bone defect, whether large or small. Through virtual planning and patient-specific CAD/CAM mesh production, extensive alveolar bone deficiencies—both horizontal and vertical can be repaired safely and predictably alongside implant placement.[32] Customized meshes, shaped using 3D patient models, enhance proper adaptation to the alveolar bone. This approach has demonstrated up to a 90% bone regeneration rate for vertical bone deficiencies. Studies indicate that patient-specific titanium meshes can facilitate significant bone augmentation in complex defects, with improvements of up to 11.48 mm horizontally and 8.90 mm vertically. This evidence suggests that laser-sintered CAD/CAM meshes are a reliable alternative to traditional bone grafting methods for treating extensive atrophic alveolar ridges.[33]



Three-dimensionally printed titanium mesh and digitally preformed titanium mesh are produced. a–d The titanium mesh is produced digitally. An illustration of the virtual alveolar defect in three dimensions. b A view of the optimally augmented alveolar ridge following three-dimensional virtual bone augmentation based on the anticipated implant site and arch shape. The virtual augmented maxilla model was prepared using titanium mesh. d The titanium mesh was prefabricated and trimmed. e–h Digital process for titanium mesh manufactured in three dimensions. Following virtual implantation, the implant's exposure to the alveolar bone defect site was noted. After three-dimensional virtual bone augmentation based on arch shape and anticipated implant position, this is a view of the ideal augmented alveolar ridge. g titanium mesh design in three dimensions based on the optimal enhanced ridge. h Three-dimensional-printed titanium mesh on the ideal augmented alveolar ridge model [21]

Aesthetic Aspects

Defects in the maxilla and mandible, often resulting from trauma, tumors, or congenital conditions, can profoundly affect both the functionality and appearance of a patient's life. Therefore, effective reconstruction of these areas is crucial. An important aspect of re-establish aesthetic and functional characteristics is the use of a grid, which facilitates and enhances 3D bone reconstruction.[34]

Digital planning and customized meshes play a crucial role in maintaining bone shape and ensuring accurate graft material placement, which in turn improves the precision of bone augmentation and the alignment of maxillary structures. In particular, aesthetic considerations are vital for the anterior maxillary region.[35] Successful implant placement depends on having sufficient alveolar bone volume, and personalized meshes show promising potential for achieving both effective bone augmentation and favorable aesthetic results.[36]

In patients with indented areas of the vestibular bone, virtual planning for bone volume augmentation and the use of custom titanium meshes fabricated through 3D printing technology have demonstrated significant bone growth. After 6 months, the average augmentation was 3.7 mm (SD ±0.59), and after 12 months, it was 4.3mm (SD±0.83).[37]

When positioning a customised 3D titanium mesh, it is essential to focus on effective soft tissue management to achieve desirable aesthetic results. This involves fostering the growth of well-defined, healthy tissue that remains free of scars or fibrosis.[38]

A promising strategy for effective bone regeneration in aesthetic regions is the implementation of a fully digital protocol, already used by some clinicians. This approach combines custom titanium meshes with prosthetically guided regeneration (PGR) to achieve reliable and satisfying outcomes.[39]

Overlaying a digital diagnostic wax-up can make the bone reconstruction process prosthetically guided, helping to maintain an adequate buccal cortical bone and ensuring a satisfactory aesthetic result.[40]

Clinical Success and Complications

Virtual planning and the creation of customized grids, along with flap design and management, are essential for achieving clinical success in the Guided Bone Regeneration (GBR) procedure. Although individualized titanium meshes are more rigid than standard ones, there remains a possibility of mesh exposure, even with the use of advanced digital techniques.[42]

This may result from mechanical stress on the mucosal tissue flap, incorrect placement of removable prostheses post-surgery, or difficulties associated with the learning curve of digital software and grid-design processes.[43]

Therefore, a careful approach is necessary to ensure the clinical success of the procedure and prevent complications. Research indicates that using a resorbable membrane over the customized mesh can lower the rate of healing complications, from 33.3% to 13.3%.[44]

Management of Early and Late Complication

In cases of mesh exposure, effective management can still result in successful GBR outcomes. Treatment typically involves either pharmacological or mechanical interventions. When mesh exposure take place within the first 4 weeks after surgery, it is managed with chlorhexidine 0.2% (CHX) gel, in use two to four times daily. This is followed by curettage of the exposed area to promote tissue healing. Provided that the treatment is carried out correctly, there are generally no restrictions on bone augmentation for implant placement. [45]

Alternatively, the literature indicates that CHX mouthwashes or CHX sprays with varying concentrations can also be used. However, CHX gel preparations tend to be more effective than mouthwashes.[46]

When a graft infection is suspected, topical antibiotic treatment becomes important. However, the literature rarely reports the use of antibiotics for mesh exposure. In cases of mesh exposure, prompt removal of the mesh is necessary due to infection and pus. Maintaining plaque control and practicing proper oral hygiene are crucial at this stage. Therefore, saline rinses and brushing with a toothbrush are effective for removing plaque. [45]

For managing late mesh exposure, applying CHX 0.2% or, in some cases, 1% gel twice daily until tissue healing is observed can be effective and help preserve the mesh. Additionally, mechanically smoothing the edges of the mesh using carbide or diamond burs facilitates secondary wound healing.[47]

IV. Conclusion

3D-printed titanium mesh represents a major advancement in guided bone regeneration (GBR). Its customizability ensures a precise fit to the patient's anatomical needs, enhancing surgical outcomes. The mesh combines titanium's strength and biocompatibility with a porous design that supports effective bone ingrowth and healing. This innovation reduces complications such as mesh exposure and infection, thanks to its optimal fit and structural stability. As 3D printing technology continues to evolve, the benefits of 3D-printed titanium meshes are expected to grow, offering even greater potential for improving bone regeneration and surgical success.

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