



Customized 3D-printed polycaprolactone (PCL) scaffolds for guided bone regeneration in oral Implantology: A narrative and methodology-based comparative review

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Abstract

Guided Bone Regeneration (GBR) is one of the key components of contemporary dental treatments for the restoration of alveolar bone before the placement of an implant. In the past few years, the advent of patient-specific, 3D-printed polycaprolactone (PCL) scaffolds has made a remarkable advance in this field; these custom-made scaffolds now have the potential to significantly enhance the outcome of bone regeneration by conforming to the anatomical needs of the patient. This narrative review describes the existing 3D-printed PCL membranes and scaffolds used in GBR, covering topics such as design and fabrication techniques, biological compatibility, mechanical properties, and degradation characteristics. A comparison is made with standard collagen membranes, noting the advantages and potential shortcomings of this technology. A mixed methodology combining clinical case evaluations, *in vitro* studies, *in vivo* animal studies, and an extensive literature review was designed. The PCL scaffold was manufactured using additive technology, aminolyzed with gelatin, and evaluated concerning volumetric and histological outcomes in a staged ridge augmentation procedure. The scaffold shown excellent biocompatibility, structural strength, and osteoconductivity after surface modification. An impressive volumetric increase of 108.4% in bone formation was recorded, with favorable histological integration achieved without any significant inflammation or surgical complications. These findings highlight the potential of custom 3D-printed PCL scaffolds as a practical and advanced alternative for GBR. Tailoring to the unique anatomy of each patient enhances regenerative outcomes, thus sagging towards an improved predictability of the surgical procedures. Meanwhile, other challenges still lie ahead, like relatively slow biodegradation of the PCL, regulatory issues, and high production cost, all of which should be critically examined and eliminated to guarantee greater clinical acceptance.

Keywords: Guided bone regeneration (GBR), 3D printing, polycaprolactone (PCL) scaffold, alveolar ridge augmentation, dental implantology, bone tissue engineering

Introduction

To answer your question, bone defects of big size pose significant clinical challenges owing to their etiology, and trauma, tumor excision, or cleft-type craniofacial anomalies based on intrinsic regenerative capability of the body [1]. Bone grafting is an important component of craniofacial surgery, particularly where it helps tooth eruption and orthodontic movement, in cleft palate repairs [2]. Autologous bone grafting is considered the gold standard for grafting; however, the process is hindered because of several factors, such as limited availability of donors, morbidity of the donor sites, increased time of surgery, chances of graft failure, complications related to anaesthesia, and certain aesthetic issues in view of the paediatric age group [3, 4]. In situations wherein using autologous grafting is ill-advised, tissue engineering has emerged as another alternative, which essentially utilizes biomaterials, either solely or in combination with cellular components, to restore or augment biological functions [5].

Although scaffold characteristics afforded great potential to successfully carry tissues, our knowledge on how scaffold properties influence bone regeneration is still uncompleted. The field of research involving 3D-printed polycaprolactone

(PCL) scaffolds has gained momentum; however, factors such as highly variable results from *in vitro* and *in vivo* tests, lack of standard processes for scaffold fabrication, and absence of comparative studies to commercial collagen membranes seem to be preventing the clinical translation of research [6, 7, 8]. Furthermore, the areas associated with the slow degradation rate and poor bioactivity of PCL present other dilemmas to be considered [9]. Hence, there is a need for a systematic assessment of said recent studies to elucidate material-cell interactions and pinpoint key design parameters steering toward scaffold performance [10].

The review is sought for evaluating critically how scaffold properties such as morphology, surface topography, porosity, surface chemistry, and architectural design affect osteogenic outcomes in bone regeneration. It will concentrate on assessing the comparative performance of 3D-printed PCL membranes against commercial collagen-based scaffolds with respect to *in vitro* studies, animal models, and available clinical data. This study aims to provide a roadmap for the future fabrication of optimized scaffolds for guided bone regeneration in the reconstruction of craniofacial deformities and other major bone defects

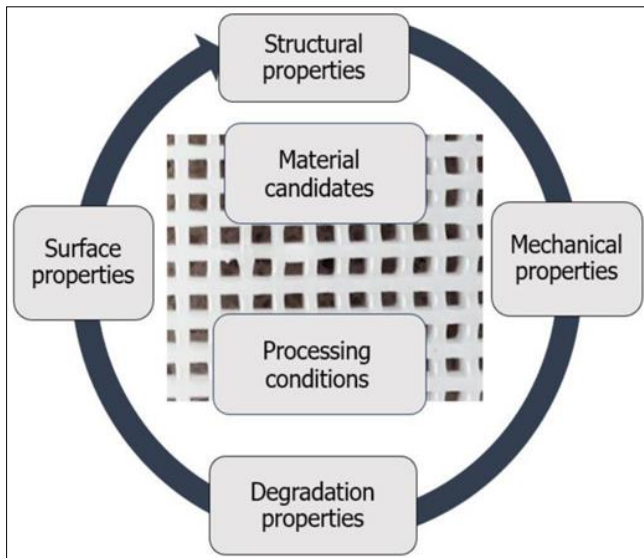


Fig 1: Key parameters in 3D-printed PCL scaffold fabrication.

Literature Review

Guided bone regeneration (GBR) has been widely employed in conjunction with the placement of polycaprolactone (PCL)-based membrane implants, isolated from non-osteogenic soft tissue invasion by means of barrier membranes in order to facilitate proliferation of osteoprogenitor cells and bone regeneration in that space [11]. In advanced computer-assisted surgery, biomaterials-enhanced integration, and digital manufacturing, 3D-printing has made great inroads in clinical GBR, particularly in oral implantology [12, 13].

The patient-specific ability of 3D printing makes it possible to produce devices designed to personal engineering, physical-science, and biological individuality in implant-prosthetic rehabilitation and structural body regeneration therapy [14]. Besides, it has been researched that such technologies reduce surgical time and minimize surgical complications and notice improved conformity with anatomical structures compared to the traditional GBR techniques [15]. Accordingly, narrative reviews have aimed to explore the integration of digital radiographic workflows, material selections, and the manufacturing-controlled properties of 3D-printed meshes, membranes, bone grafts, and dental implants used in GBR [16]. Clinical applications are concerned with the evaluation of histological outputs, complication profiles, and patient-reported outcomes, which may involve both short- and long-range assessments [17, 18]. Considering scaffold fabrication, polycaprolactone (PCL) as a material has gained much attention owing to its favorable degradation behavior. Under physiological conditions, hydrolytic degradation of its ester linkages continues in PCL, which is an aliphatic, semi-crystalline type of polymer having its melting point above human body temperature [19]. Hence, under *in vivo* conditions, PCL exhibits elastomeric behavior, owing to which it provides additional toughness and mechanical properties [20].

PCL has been shown to be non-toxic and biocompatible, both required for any material applied clinically to bone regeneration [21]. Moreover, it is available in the market, cheap, and can be easily manipulated to modify its chemical, biological, and physicochemical properties regarding degradation kinetics and mechanical strength [22]. PCL has been demonstrated to be non-toxic and

biocompatible, qualities that are essential for materials used in clinical applications involving bone regeneration [21]. Moreover, it is readily available, cost-effective, and amenable to modifications that can tailor its chemical, biological, and physicochemical properties, including its degradation kinetics and mechanical strength [22]. The typical degradation period of PCL ranges from two to three years, enabling its application in hard tissue engineering, particularly in load-bearing environments. However, despite its structural benefits, the material has been reported to exhibit limited osteoconductivity due to its hydrophobic surface characteristics, which may hinder cellular adhesion and subsequent bone tissue integration [19, 21].

Current State of the Art

1. Overview of Existing Devices and Technologies

Several commercial barrier membranes for GBR are currently in use, including collagen-based membranes such as Bio-Gide® (Geistlich Pharma), Jason® Membrane (Botiss), and titanium mesh systems. These devices are characterized by high biocompatibility and favorable tissue integration but exhibit limitations in mechanical strength and customization potential [21].

2. Technological Advancements

These advancements allow 3D printing technologies to manufacture patient-specific scaffolds that can be altered in morphology and mechanical behavior. Notable materials include polycaprolactone (PCL), which provides slow degradation, mechanical stability, and design flexibility. Recent case studies have demonstrated promising volumetric gains and soft-tissue integration following the use of 3D-printed PCL scaffolds [22, 23]. Comparatively, these constructs outperform traditional membranes in terms of defect-specific adaptability and mechanical retention [24].

3. Regulatory and Clinical Landscape

The use of PCL scaffolds has been investigated in both preclinical models and early-phase clinical trials. While PCL is FDA-approved for some medical applications, its use in GBR is still undergoing regulatory scrutiny. Clinical studies have shown minimal post-operative complications and favorable esthetic healing outcomes [25, 26, 27]. Regulatory pathways remain complex due to the personalized nature of 3D-printed devices, requiring case-by-case validations.

Mechanism of Action and Design Considerations

1. Design Principles

The design of 3D-printed PCL scaffolds typically involves computer-aided modeling to match patient-specific defects. Structural parameters such as pore size, interconnectivity, and layer thickness are modulated to optimize cellular infiltration and nutrient diffusion. Mechanical reinforcement is achieved by altering infill density and geometry, often verified through finite element simulations [28].

2. Performance and Efficacy

In a clinical case involving a 46-year-old male with a type-4 horizontal ridge defect, a customized PCL scaffold was used for ridge augmentation. Post-operative evaluations revealed a volumetric gain of 108.4% (336.28 mm³ to 364.69 ± 2.53 mm³). Histological analysis indicated mature bone formation, absence of inflammation, and integration of residual graft particles [29]. These findings were consistent

with preclinical studies in canine tibia models, where PCL/gelatin constructs demonstrated enhanced fibrosis grading and osteoconduction [30].

Comparative Insights

1. Comparison with Existing Devices

PCL scaffolds have shown superior mechanical stability compared to resorbable collagen membranes and better biointegration than titanium meshes. However, their slow degradation and hydrophobic nature can delay full tissue remodeling [31]. Despite these limitations, their patient-specific geometry offers a key advantage in complex defect management.

2. Cost and Accessibility

Although 3D-printed PCL scaffolds require higher initial manufacturing costs and specialized imaging for design, the reduced need for secondary surgeries and lower complication rates may offset expenses in the long term. Current limitations include limited market penetration and the need for customized fabrication labs [32, 33].

Challenges and Limitations

Key challenges include the slow degradation rate of PCL, regulatory uncertainties for custom implants, and variable clinical outcomes. Moreover, standardized protocols for scaffold design and testing are lacking, impeding large-scale comparative studies. Additional notable issues have something to do with immune modulation, long-term mechanical system sustenance, and financial feasibility for popularization [34, 35, 36].

Discussion

The introduction of 3D printing into guided bone regeneration (GBR) greatly supports surgical methods in oral implantology that are accurate and patient-specific. In this respect, PCL-based scaffolds represent versatile platforms, considering their variable mechanical characteristics, good biocompatibility, and slow biodegradability. The present narrative focuses on the application of customized 3D-printed PCL scaffolds, especially concerning the fabrication method, biological performance, and clinical feasibility.

The case report involving a patient-specific PCL scaffold implantation demonstrated encouraging outcomes, including volumetric gain exceeding 100%, favorable histological integration, and minimal post-operative complications. The scaffold provided effective space maintenance and supported new bone formation with minimal inflammatory response, corroborating findings from previous animal and *in vitro* studies [21, 22, 23]. Moreover, the application of gelatin bio-coating through aminolysis proved to have a significant contribution to the enhancement of cellular attachment, which is an encouraging feature to overcome the absolute hydrophobicity and limited osteoconductivity of PCL [24, 35, 26].

Histological analysis revealed mature lamellar bone intermixed with residual graft particles, with an absence of chronic inflammatory cells, indicating good biocompatibility and osteointegration. Visualization of bone multicellular units (BMUs) and haversian systems showed active remodeling, necessary for long-term functional regeneration. These observations align with prior literature that emphasizes the importance of scaffold porosity, surface

modification, and mechanical congruity with the host site to optimize regenerative outcomes [27, 28, 29].

Despite these promising results, several limitations must be acknowledged. The long degradation time of PCL, while beneficial for mechanical stability, may limit its application in sites requiring rapid turnover or in younger patients with accelerated bone metabolism. Also, regulatory hurdles, increased manufacturing costs, and a lack of coherent fabrication standards act as barriers to the widespread clinical adoption [30, 31, 32]. Thus, there remains a dire need for multicenter randomized clinical trials that confirm our findings and set the grounds for standard protocols for scaffold design, surface modifications, and their clinical use.

Conclusion

The use of 3D-printed PCL scaffolds in GBR signifies a turning point in regenerative dentistry, providing an individualized, biocompatible, and structurally stable option compared to the current membranes. The highlighted clinical case shows that the customized PCL scaffolds as effective tools in promoting the augmentation of the alveolar ridges toward positive histological and volumetric outcomes. However, research will have to continue to address issues related to bioactivity, degradation kinetics, and clinical standardization. Future directions should focus on bioactive agent incorporation, improvements in the resorption rates of scaffolds, and more exhaustive clinical validation for broader applicability and long-term success in oral implant rehabilitation.

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