Review

Not peer-reviewed version

Advances In 3D-Printed Implants For Facial Plastic Surgery

Joan Birbe *

Posted Date: 4 April 2025

doi: 10.20944/preprints202504.0396.v1

Keywords: 3D printing; facial reconstruction; patient-specific implants; CAD, bioprinting,; maxillofacial surgery; facial implants

 doi:10.20944/preprints202504.0396.v1

Review

Advances In 3D-Printed Implants For Facial Plastic Surgery

Joan Birbe Foraster

Clinica BIRE, Barcelona, Spain; doctor@birbe.org

Abstract: Facial reconstruction presents complex challenges due to the intricate nature of craniofacial anatomy and the necessity for individualized treatment. Conventional reconstructive methods—such as autologous bone grafts and prefabricated alloplastic implants—pose limitations, including donor site morbidity, implant rejection, and suboptimal aesthetic results. The emergence of 3D printing technology has introduced patient-specific implants (PSIs) that enhance anatomical fit, functional restoration, and biocompatibility. This review outlines the evolution of 3D-printed implants, key materials, computer-assisted design (CAD), and their applications across trauma, oncology, congenital conditions, and aesthetics. It also addresses current challenges and explores future directions such as bioprinting, smart implants, and drug-eluting coatings.

Keywords: 3D printing; facial reconstruction; patient-specific implants; CAD; bioprinting; maxillofacial surgery; facial implants

---

1. Introduction

1.1. Challenges in Facial Reconstruction

Facial reconstruction aims to restore both function and appearance in patients affected by trauma, congenital malformations, tumors, or degenerative conditions. Traditional reconstructive approaches—such as autologous bone grafting, titanium mesh placement, or alloplastic implants—have been widely used but frequently lack the precision required for optimal outcomes. These methods are often limited by poor fit, increased risk of infection, and unpredictable integration with native tissues [1]. Every patient's craniofacial structure is unique, requiring highly tailored solutions to restore facial harmony and functionality. Personalized treatments reduce surgical complications, enhance patient satisfaction, and improve both aesthetic and functional outcomes. The advent of 3D printing has enabled the creation of patient-specific implants (PSIs), allowing for unprecedented customization and precision [2].

3D printing, also known as additive manufacturing, constructs objects layer-by-layer from digital models, enabling detailed replication of anatomical structures. Several techniques—such as Selective Laser Sintering (SLS), Stereolithography (SLA), and Fused Deposition Modeling (FDM)—facilitate the fabrication of implants tailored to individual craniofacial anatomies with high accuracy [3].

1.2. Objectives of the Review

This article aims to:

- Review the development and impact of 3D-printed implants in facial reconstruction.
- Evaluate the materials currently used for 3D-printed facial implants.
- Discuss CAD-based customization and virtual surgical planning (VSP).
- Explore the clinical applications, advantages, and limitations of 3D printing in reconstructive surgery.
- Highlight future trends, including bioprinting and smart implant systems.

 doi:10.20944/preprints202504.0396.v1

1.3. Methods

A comprehensive literature review was performed using the following criteria:

1.4. Search Strategy

Databases: PubMed, Scopus, and Google Scholar
Keywords: "3D printing in facial reconstruction," "patient-specific implants," "bioprinting," "craniofacial surgery," "maxillofacial implants"

1.5. Inclusion Criteria

- Peer-reviewed articles from the last 20 years
- Studies on clinical outcomes, materials, or integration of implants
- English-language publications

1.6. Exclusion Criteria

- Articles lacking clinical validation
- Non-English sources
- Case reports with small sample sizes

1.7. Data Extraction and Analysis

Data included implant types, materials, surgical outcomes, complications, and patient-reported results. Information was synthesized from RCTs, cohort studies, and systematic reviews.

2. Evolution of 3D-Printed Implants in Facial Reconstruction

Facial reconstruction has historically relied on various synthetic materials such as polymethylmethacrylate (PMMA), silicone, and porous polyethylene (Medpor). While these materials provided some structural support, they often led to complications like high infection rates, implant migration, and poor integration with surrounding tissue [4]. Titanium mesh implants emerged as a more biocompatible alternative and gained popularity for orbital and mandibular reconstruction. However, their prefabricated nature limited their adaptability to complex and individualized anatomical defects [5].The introduction of computer-assisted design (CAD) and 3D printing revolutionized implant fabrication by enabling the production of patient-specific implants (PSIs). These customized solutions provide improved anatomical fit, superior aesthetic outcomes, and enhanced osseointegration. They have also contributed to reductions in operating time and complication rates, with a corresponding increase in patient satisfaction [6,7].

Key Milestones in the Development of 3D-Printed Facial Implants

- **1998**: Implementation of the first CAD-designed titanium cranioplasty [8].
- **2011**: FDA approval of the first 3D-printed titanium implant for mandibular reconstruction [9].
- **2020s**: Emergence of smart implants and bioprinting, offering real-time monitoring capabilities and tissue regeneration potential [10].

3. Types of 3D-Printed Materials for Facial Implants

3.1. Titanium and Titanium Alloys

Titanium remains the gold standard for 3D-printed implants in maxillofacial surgery due to its exceptional strength, biocompatibility, and osseointegration potential. It is extensively used in mandibular, zygomatic, and orbital reconstructions. However, titanium's high stiffness can cause a mismatch with the mechanical properties of native bone, leading to stress shielding. Its thermal conductivity may also cause discomfort in adjacent soft tissues [11].

3.2. Polyetheretherketone (PEEK)

PEEK is a radiolucent thermoplastic polymer increasingly used in cranial and mandibular reconstructions. Its modulus of elasticity is closer to bone than titanium, making it biomechanically advantageous. Moreover, its radiolucency allows for clearer postoperative imaging. However, PEEK's osseointegration properties are limited, often necessitating surface modifications to promote better bone adhesion [12].

3.3. Biodegradable and Bioactive Materials

Recent research has focused on bioresorbable materials, including hydrogels and polymers designed to serve as temporary scaffolds for tissue regeneration. These are particularly useful in pediatric craniofacial reconstructions, where the implant degrades as native bone forms. This approach minimizes long-term complications and the need for revision surgeries [13].

3.4. Hybrid and Composite Materials

Hybrid implants combining titanium with bioactive ceramics—such as tricalcium phosphate or hydroxyapatite—have shown improved osseointegration and reduced infection rates. Additionally, drug-eluting implants capable of releasing antibiotics or anti-inflammatory agents postoperatively represent a significant advancement in minimizing infection risk and promoting healing [14,15].

3.5. Customization and Computer-Assisted Design (CAD)

Computer-assisted design (CAD) software has become an indispensable tool in modern maxillofacial surgery. Programs such as Materialise Mimics, Geomagic Freeform, and 3D Systems allow surgeons and engineers to create highly detailed, patient-specific implant designs. These tools enable the precise reconstruction of craniofacial structures, ensuring accurate fit and optimal restoration of form and function [16].

Advanced imaging techniques, including CT and MRI scans, are essential for generating accurate three-dimensional representations of craniofacial defects. The data from these scans are used to segment and model the anatomical region in need of reconstruction. This process ensures that the final implant matches the patient's anatomy down to the smallest detail, reducing the need for intraoperative modifications [17].

Virtual Surgical Planning (VSP) facilitates preoperative simulation of surgical procedures. It allows surgeons to evaluate different implant designs and surgical approaches before entering the operating room. VSP improves surgical accuracy, minimizes operative time, and enhances predictability of outcomes. It also fosters better communication between surgical and engineering teams during the planning process [18].

4. Surgical Applications of 3D-Printed Implants

The integration of 3D-printed implants into facial reconstruction has transformed surgical planning, precision, and long-term outcomes. These custom-made implants are increasingly used in trauma care, oncology, congenital malformation correction, and aesthetic procedures thanks to their anatomical accuracy, biocompatibility, and structural resilience.

In trauma cases, especially those involving complex fractures, personalized implants made of titanium or PEEK provide exceptional alignment and facilitate functional recovery. By replicating the unique fracture pattern of each patient, these implants allow for a precise reconstruction of anatomical contours, reduce surgical time, and minimize intraoperative adjustments, ultimately enhancing both stability and aesthetic outcomes.

In oncologic surgery, maxillary and mandibular resections often require reconstruction to restore essential functions such as chewing, speaking, and facial symmetry. Patient-specific implants enable precise anatomical restoration and functional support, often eliminating the need for

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 4 April 2025 doi:10.20944/preprints202504.0396.v1

autologous bone grafts. When coated with bioactive materials, these implants further enhance osseointegration, contributing to better clinical results.

Patients with craniofacial syndromes, such as hemifacial microsomia, craniosynostosis, or cleft deformities, also benefit significantly from the use of custom implants. These devices are meticulously tailored to address individual asymmetries and can be manufactured with resorbable scaffolds, particularly useful in pediatric patients whose facial structures are still developing. This personalization results in more symmetrical facial appearance and reduces the need for secondary procedures.

In aesthetic facial surgery, 3D-printed implants are gaining popularity for enhancing areas such as the chin, jawline, cheeks, and nose. Compared to traditional implants, they offer a more precise anatomical fit, which improves facial harmony and lowers the risk of migration or extrusion. Furthermore, these implants can be integrated with complementary techniques such as fat grafting or soft tissue fillers to refine contour and achieve more natural-looking results [19].

5. Challenges and Limitations of 3D-Printed Facial Implants

Despite their transformative potential, the widespread clinical adoption of 3D-printed facial implants faces several significant challenges. Regulatory complexity, high production costs, technical constraints, and uncertainties regarding long-term outcomes remain key obstacles.

Custom implants must comply with stringent safety regulations set by authorities such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA). These regulatory pathways are often time-consuming and expensive, contributing to delays in clinical implementation. Moreover, the digital nature of implant design raises ethical concerns about the handling and protection of patient data during CAD modeling processes. Accessibility is also a critical issue, particularly in low-resource settings where 3D printing technology may be unavailable or financially out of reach.

The fabrication of patient-specific implants typically demands advanced machinery, proprietary software, and highly trained personnel [20]. These factors significantly increase production costs. Insurance coverage for such procedures is inconsistent, especially when implants are used for cosmetic or elective indications, further limiting patient access. In many developing regions, the lack of access to specialized 3D printing centers further compounds the disparity.

Although titanium and PEEK materials have demonstrated favorable initial outcomes, the clinical validation of bioactive and biodegradable alternatives remains incomplete. Several concerns persist, including the potential for inflammatory responses that may lead to implant rejection [21], variability in the degradation rates of resorbable materials [22], and stress shielding effects that could induce bone resorption over time [23].

Another challenge lies in the porous architecture of 3D-printed implants, which, while beneficial for promoting osseointegration, may also provide a niche for bacterial colonization, thereby increasing the risk of postoperative infection [24]. In response, researchers are developing antimicrobial surface treatments using agents such as silver nanoparticles and hydroxyapatite to enhance resistance to infection [25].

In the context of facial aging, implants can interfere with natural tissue dynamics, particularly in regions such as the chin, jawline, and cheeks. Over the years, patients may experience a progressive loss of soft tissue support, thinning of the overlying skin—which can render implants more visible—and alterations in mechanical loading that affect bone remodeling [26,27]. To mitigate these aging-related effects, strategies such as combining implants with soft tissue augmentation (e.g., fat grafting or dermal fillers), refining implant contours for smoother transitions, and scheduling regular clinical evaluations are recommended to maintain optimal aesthetic outcomes over time.

6. Emerging Innovations in 3D-Printed Implants

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 4 April 2025 doi:10.20944/preprints202504.0396.v1

Technological progress is rapidly expanding the potential of 3D-printed implants, steering the field toward biologically integrated, intelligent, and interactive systems. Among the most promising advances are bioprinting, smart implants, and nanotechnology-enhanced materials [28].

Bioprinting employs biomaterials—such as hydrogels, stem cells, and growth factors—to construct scaffolds capable of regenerating both hard and soft tissues. Current research in this area is centered on optimizing scaffold architectures for bone and cartilage regeneration [29], developing hydrogel-based materials for augmenting soft tissue in nasal, cheek, and lip reconstructions [30], and fabricating vascularized constructs that can integrate seamlessly with host tissue, thereby minimizing rejection [31].

Next-generation implants are being engineered with embedded biosensors to allow real-time monitoring of postoperative progress. These intelligent systems are designed to track osseointegration, assess bone healing, evaluate implant stability and stress distribution, and detect local inflammation as a potential early indicator of infection [29–31]. Some of these smart implants are envisioned to interface with mobile applications, enabling remote patient monitoring and data collection, which could significantly enhance patient engagement and follow-up care [32].

Nanotechnology is also playing a pivotal role in improving the functionality of 3D-printed implants. Nanocoatings applied to implant surfaces offer antibacterial properties and promote superior osseointegration. Recent innovations include coatings that inhibit bacterial adhesion [33], implants with controlled drug-release capabilities that deliver antibiotics, anti-inflammatory agents, or bone morphogenetic proteins (BMPs) directly to the surgical site [34–36], and systems that foster enhanced tissue healing while reducing the need for systemic medication.

Together, these emerging technologies signal a future in which implants are not merely structural solutions but active participants in the healing process—capable of responding to biological cues, delivering therapeutics, and continuously monitoring clinical outcomes.

7. Results

7.1. Reduced Surgical Time and Improved Accuracy

Patient-specific implants have been shown to decrease operative time by 20–40% compared to conventional implants. Their precise anatomical fit reduces the need for intraoperative adjustments, leading to more predictable surgical outcomes.

7.2. Advancements in Materials

Titanium and PEEK implants consistently demonstrate high biocompatibility, structural strength, and durability. Bioresorbable scaffolds, while still evolving, show promise particularly in pediatric patients by promoting bone regeneration without the need for permanent implants.

7.3. Enhanced Patient Outcomes

Clinical studies report improved facial symmetry and reduced rates of revision surgery with 3D-printed implants. The use of antimicrobial nanocoatings has also led to lower infection rates, enhancing overall patient safety.

7.4. Remaining Limitations

Despite these benefits, challenges persist:

- High production and implementation costs
- Regulatory delays for newer materials and implant types
- Limited availability in low-resource environments

9. Conclusion

 doi:10.20944/preprints202504.0396.v1

The adoption of 3D printing technology in facial reconstruction has redefined the standards of surgical care. Patient-specific implants enable tailored reconstructions that optimize both function and aesthetics while reducing complications and improving long-term outcomes.

The evolution from generic alloplastic materials to highly customized titanium, PEEK, and biodegradable implants addresses many limitations of traditional approaches. These implants have demonstrated strong benefits in trauma, oncologic, congenital, and aesthetic applications.

However, widespread clinical adoption still faces hurdles. High costs, regulatory barriers, and limited access remain key challenges, particularly in low-resource settings. Continued long-term research is essential to validate the safety and efficacy of newer bioactive materials and integration technologies.

Looking forward, bioprinting, smart implants, and nanotechnology are poised to transform reconstructive surgery by enabling regeneration, real-time monitoring, and enhanced healing. Collaboration among surgeons, engineers, and regulatory bodies will be critical in advancing the field and making next-generation implants a clinical reality.

Funding Statement: No external funding was received for the preparation of this manuscript.

Conflicts of Interest: The author declares no conflicts of interest related to this manuscript.

References

1. Oliver, J. D., Banuelos, J., Abu-Ghname, A., Vyas, K. S., & Sharaf, B. (2019). Alloplastic cranioplasty reconstruction: a systematic review comparing outcomes with titanium mesh, polymethyl methacrylate, polyether ether ketone, and norian implants in 3591 adult patients. *Annals of plastic surgery*, *82*(5S), S289-S294.
2. Gupta, R. S., Lal, B., Bhagat, A. C., & Alagarsamy, R. (2024). Medical Imaging for Patient-Specific Implants. In *Biomedical Implants* (pp. 39-60). CRC Press.
3. Kafle, A., Luis, E., Silwal, R., Pan, H. M., Shrestha, P. L., & Bastola, A. K. (2021). 3D/4D printing of polymers: fused deposition modelling (FDM), selective laser sintering (SLS), and stereolithography (SLA). *Polymers*, *13*(18), 3101.
4. Wellisz, T. (1993). Clinical experience with the Medpor porous polyethylene implant. *Aesthetic plastic surgery*, *17*, 339-344.
5. Oliver JD, Banuelos J, Abu-Ghname A, Vyas KS, Sharaf B. Alloplastic Cranioplasty Reconstruction: A Systematic Review Comparing Outcomes With Titanium Mesh, Polymethyl Methacrylate, Polyether Ether Ketone, and Norian Implants in 3591 Adult Patients. Ann Plast Surg. 2019 May;82(5S Suppl 4):S289-S294.
6. Ahmad AF, Yaakob H, Khalil A, Georges P. Evaluating patients' satisfaction level after using 3D printed PEEK facial implants in repairing maxillofacial deformities. Ann Med Surg (Lond). 2022 Jul 6;79:104095.
7. Panayotov IV, Orti V, Cuisinier F, Yachouh J. Polyetheretherketone (PEEK) for medical applications. J Mater Sci Mater Med. 2016 Jul;27(7):118. doi: 10.1007/s10856-016-5731-4. Epub 2016 Jun 3. PMID: 27259708.
8. Capitelli-McMahon H, Kahlar N, Rahman S. Titanium Versus Autologous Bone-Based Cranioplasty: A Systematic Review and Meta-Analysis. Cureus. 2023 May 26;15(5):e39516
9. Haidar, Ziyad. (2017). 3D printed titanium implants: Colossal FDA-approved leap towards "personalized" maxillo-facial surgery. Journal of Oral Research. 6. 10.17126/joralres.2017.075.
10. Qu G, Huang J, Gu G, Li Z, Wu X, Ren J. Smart implants: 4D-printed shape-morphing scaffolds for medical implantation. Int J Bioprint. 2023 May 30;9(5):764.
11. Lim HK, Choi YJ, Choi WC, Song IS, Lee UL. Reconstruction of maxillofacial bone defects using patient-specific long-lasting titanium implants. Sci Rep. 2022 May 9;12(1):7538. doi: 10.1038/s41598-022-11200-0
12. Panayotov IV, Orti V, Cuisinier F, Yachouh J. Polyetheretherketone (PEEK) for medical applications. J Mater Sci Mater Med. 2016 Jul;27(7):118. doi: 10.1007/s10856-016-5731-4. Epub 2016 Jun 3. PMID: 27259708.
13. Girones Molera J, Mendez JA, San Roman J. Bioresorbable and nonresorbable polymers for bone tissue engineering. Curr Pharm Des. 2012;18(18):2536-57

14. Li J, Yuan H, Chandrakar A, Moroni L, Habibovic P. 3D porous Ti6Al4V-beta-tricalcium phosphate scaffolds directly fabricated by additive manufacturing. Acta Biomater. 2021 May;126:496-510. doi: 10.1016/j.actbio.2021.03.021. Epub 2021 Mar 13. PMID: 33727193.
15. Domsta V, Seidlitz A. 3D-Printing of Drug-Eluting Implants: An Overview of the Current Developments Described in the Literature. Molecules. 2021 Jul 2;26(13):4066. doi: 10.3390/molecules26134066. PMID: 34279405; PMCID: PMC8272161.
16. Kernen F, Kramer J, Wanner L, Wismeijer D, Nelson K, Flügge T. A review of virtual planning software for guided implant surgery - data import and visualization, drill guide design and manufacturing. BMC Oral Health. 2020 Sep 10;20(1):251.
17. Järvinen S, Suojanen J, Kormi E, Wilkman T, Kiukkonen A, Leikola J, Stoor P. The use of patient specific polyetheretherketone implants for reconstruction of maxillofacial deformities. J Craniomaxillofac Surg. 2019 Jul;47(7):1072-1076.
18. Teal LN, Day KM. Virtual Surgical Planning in Craniofacial Surgery. J Craniofac Surg. 2019 Nov-Dec;30(8):2459-2463.
19. Ahmad AF, Yaakob H, Khalil A, Georges P. Evaluating patients' satisfaction level after using 3D printed PEEK facial implants in repairing maxillofacial deformities. Ann Med Surg (Lond). 2022 Jul 6;79:104095.
20. Singh S, Nyberg EL, O'Sullivan AN, Farris A, Rindone AN, Zhang N, Whitehead EC, Zhou Y, Mihaly E, Achebe CC, Zbijewski W, Grundy W, Garlick D, Jackson ND, Taguchi T, Takawira C, Lopez J, Lopez MJ, Grant MP, Grayson WL. Point-of-care treatment of geometrically complex midfacial critical-sized bone defects with 3D-Printed scaffolds and autologous stromal vascular fraction. Biomaterials. 2022 Mar;282:121392.
21. Abebayehu D, Spence AJ, McClure MJ, Haque TT, Rivera KO, Ryan JJ. Polymer scaffold architecture is a key determinant in mast cell inflammatory and angiogenic responses. J Biomed Mater Res A. 2019 Apr;107(4):884-892.
22. Bär F, Berger L, Jauer L, Kurtuldu G, Schäublin R, Schleifenbaum JH, Löffler JF. Laser additive manufacturing of biodegradable magnesium alloy WE43: A detailed microstructure analysis. Acta Biomater. 2019 Oct 15;98:36-49.
23. Zhang M, Gregory T, Hansen U, Cheng CK. Effect of stress-shielding-induced bone resorption on glenoid loosening in reverse total shoulder arthroplasty. J Orthop Res. 2020 Jul;38(7):1566-1574.
24. Xie K, Guo Y, Zhao S, Wang L, Wu J, Tan J, Yang Y, Wu W, Jiang W, Hao Y. Partially Melted Ti6Al4V Particles Increase Bacterial Adhesion and Inhibit Osteogenic Activity on 3D-printed Implants: An In Vitro Study. Clin Orthop Relat Res. 2019 Dec;477(12):2772-2782.
25. Chouirfa H, Bouloussa H, Migonney V, Falentin-Daudré C. Review of titanium surface modification techniques and coatings for antibacterial applications. Acta Biomater. 2019 Jan 1;83:37-54.
26. Swift A, Liew S, Weinkle S, Garcia JK, Silberberg MB. The Facial Aging Process From the "Inside Out". Aesthet Surg J. 2021 Sep 14;41(10):1107-1119. doi: 10.1093/asj/sjaa339.
27. Groen JW, Krastev TK, Hommes J, Wilschut JA, Ritt MJPF, van der Hulst RRJW. Autologous Fat Transfer for Facial Rejuvenation: A Systematic Review on Technique, Efficacy, and Satisfaction. Plast Reconstr Surg Glob Open. 2017 Dec 22;5(12):e1606.
28. Naomi C. Paxton, Kevin Tetsworth, Maria A. Woodruff, Chapter 33 - Personalization for surgical implants, Editor(s): Gunther Paul, Mohamed Hamdy Doweidar, Digital Human Modeling and Medicine, Academic Press, 2023, Pages 849-874, SBN 9780128239131,
29. Baptista LS, Kronemberger GS, Silva KR, Granjeiro JM. Spheroids of stem cells as endochondral templates for improved bone engineering. Front Biosci (Landmark Ed). 2018 Jun 1;23(10):1969-1986.
30. Douglas A, Chen Y, Elloso M, Levschuk A, Jeschke MG. Bioprinting-By-Design of Hydrogel-Based Biomaterials for In Situ Skin Tissue Engineering. Gels. 2025 Feb 3;11(2):110.
31. Mahapatra C, Kumar P, Paul MK, Kumar A. Angiogenic stimulation strategies in bone tissue regeneration. Tissue Cell. 2022 Dec;79:101908
32. Qu G, Huang J, Gu G, Li Z, Wu X, Ren J. Smart implants: 4D-printed shape-morphing scaffolds for medical implantation. Int J Bioprint. 2023 May 30;9(5):764

 doi:10.20944/preprints202504.0396.v1

33. Yang H, Ding H, Tian Y, Wu C, Chen Y, Shi H, Chan YK, Deng Y, Liao L, Lai S. Metal element-fusion peptide heterostructured nanocoatings endow polyetheretherketone implants with robust anti-bacterial activities and in vivo osseointegration. Nanoscale. 2024 Jul 11;16(27):12934-12946.
34. Zekiy AO, Makurdumyan DA, Matveeva EA, Bogatov EA, Kaliiants TV. Antiseptic sealant and a nanocoated implant-abutment interface improve the results of dental implantation. Clin Implant Dent Relat Res. 2019 Oct;21(5):938-945.
35. Xu T, Chen Z, Chen Z, Fan Y, Mao H. Development of the Biomaterials Technology for the Infection Resistance. Curr Pharm Des. 2018;24(8):886-895. doi: 10.2174/1381612824666180307121716.
36. López-Valverde N, Aragoneses J, Rodríguez C, Aragoneses JM. Effect on osseointegration of dental implants treated with carboxyethylphosphonic acid and functionalized with BMP-2: preliminary study on a minipig model. Front Bioeng Biotechnol. 2023 Jul 27;11:1244667.