

Review Article

Reimagining Maxillofacial Reconstruction: Transformative Advances in 3D Printing and Patient-Specific Implant Design

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Maxillofacial reconstructive surgery is designed to bring back function and appearance to the face following the loss of tissue due to trauma, congenital problems, and disease or tumour removals. Conventional methods for performing maxillofacial reconstruction using autografts, allografts or standard implants have some limitations like donor site issues, prolonged surgeries, poor anatomic fit, inconsistent or inadequate long-term outcomes. The 3D printing technology is emerging as a revolutionary manufacturing platform that permits the development of anatomic models, custom implants, patient-specific surgical plans, and regenerative scaffolds. Advances in imaging, computer-aided design and additive manufacturing have significantly improved post-surgical recovery, symmetry of cosmesis, and surgical accuracy. Craniofacial applications are increasingly using titanium, PEEK, biodegradable polymers, and bioactive ceramics, along with the additional use of bioprinting, smart biomaterials, and artificial intelligence workflows for reconstructive therapies of craniofacial structures. There are still many limitations, including regulatory approval, manufacturing costs, standardized materials, and a lack of long-term clinical outcome data. This review aims to summarize currently available materials; manufacturing techniques; clinical applications; major advantages and disadvantages; and future directions for 3D-printed customized implants used for maxillofacial reconstruction.

Introduction

Maxillofacial reconstruction is still considered to be one of the most challenging subspecialties within the field of modern reconstructive medicine, requiring the simultaneous restoration of structural integrity and functional activity (mouth), the maintenance or production of airway opening, the restoration of facial symmetry, and the psychosocial benefit of the patient [1,2]. Maxillofacial defects can result from high-energy traumatic injuries, congenital malformations, infections, osteonecrosis, or ablative surgery (benign/malignant) of the oral cavity or craniofacial region [3]. Millimetre-level accuracy is critical due to the effect of even small changes in dimensions on masticating and articulating speech, aligning the eyes, functioning of temporo-mandibular joint (TMJ), and achieving a harmonious facial appearance when compared with most other anatomical sites undergoing reconstruction [4,5].

Examples of traditional therapies include autografts, allografts, vascularized free flaps, and prefabricated metal implants [6,7]. While these

methods have therapeutic value as well as some limitations, such as high rates of sick leave after surgery, low rates of successful grafting, and long surgical times, all of these disadvantages have increased interest in developing individualized therapeutic alternatives capable of accurately replicating anatomy specific to each individual patient [8,9].

Consequently, three-dimensional (3D) printing has made an impact on how we do business in our day-to-day lives [10]. Clinicians can now produce customized patient-specific implants, cutting jigs, models, and regenerative scaffolds to accurately replace defects by integrating computed tomography (CT), magnetic resonance imaging (MRI), digital segmentation, virtual surgical planning, and computer-assisted design (CAD) [11,12]. The advantages of the printing methods used today, the relative properties of printed materials, the clinical usages of these materials, the significant advantages of these materials, the translational challenges of these materials, and the expected advancements that will be used to create the next generation of maxillofacial reconstruction are all discussed in this review [13,14].

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Evidence-Based Review Strategy

The narrative review conducted in this study was done by systematically searching the literature using PubMed, Scopus and Web of Science from January 2020 - March 2026. The keywords used in the search were “maxillofacial reconstruction”, “3D printing”, “patient-specific implant”, “craniofacial biomaterials”, “PEEK”, “titanium implant”, “virtual surgical planning”, “bioprinting” and “artificial intelligence”, with particular focus on Randomized Controlled Trials (RCT’s), prospective cohort studies, meta-analysis, systematic reviews and high impact translational studies [15-18]. Additionally, selected case reports and proof-of-concept type studies were also included to provide some insight to emerging technologies associated with limited evidence of clinical use. The comprehensive synthesis of the literature was performed to evaluate performance of biomaterials, additive manufacturing workflows, clinical outcomes, and obstacles to translation, and to provide future directions for customized maxillofacial reconstruction (table 1).

The evidence for patient-specific maxillofacial implants is still inconsistent. The majority of clinical data come from retrospective cohorts and case series, even though a number of systematic reviews and meta-analyses show positive results in terms of surgical accuracy, implant fit, and shorter operating times. There are very few large multicentre randomized controlled trials that compare titanium, PEEK, bioactive ceramics, and composite implant technologies. Thus, the relative strength of the underlying evidence should be taken into account when interpreting clinical outcomes.

Fundamentals of 3D Printing in Biomedical Reconstruction

Additive manufacturing (or 3D printing) creates physical objects by adding

(or fusing) material in layers according to a digital plan, compared to subtractive machining (removing material from a solid block) [21]. This technique greatly minimizes product waste, as well as allowing the creation of complicated geometries, controlled porosity, internal channels and unique customization to individual patients [22].

These attributes are vital for biomedical reconstruction due to the non-symmetrical, diverse and typically site-specific nature of biological architecture. One important clinical advantage of using additive manufacturing is to match the geometry of the implant to the native anatomy [23, 24]. The added benefit of additive manufacturing allows for decentralised production workflow, iterative design revision, and rapid prototyping.

Major printing technologies

Stereolithography (SLA): The SLA process is a highly advanced form of additive manufacturing that utilizes either lasers or UV light to cure photopolymeric resins in a layered fashion. This process produces a high quality of surface finish, allows for fine detail and precise dimensional accuracy. As a result of these characteristics, SLA is ideal for the production of accurate surgical guides, dental templates, and realistic anatomical models to be used in preoperative planning [25,26].

Selective Laser Sintering (SLS): SLS is a powder-based additive manufacturing process, utilizing layer-by-layer fusion of polymer particles given out by a laser beam of energy. It is good to design strong and lightweight parts that contain internal complex features and geometries. The complex geometries can often be achieved without a lot of manufactured support, as the powder surrounding them provides natural support [27, 28].

Fused Deposition Modeling (FDM): Fused Deposition Modeling (FDM) is an easily accessible form of additive manufacturing that produces items in layers by melting and extruding plastic material at varying tem-

Table 1: Evidence hierarchy and literature selection criteria for personalized maxillofacial reconstruction [19,20]

Component	Description	Evidence Level	Relative Strength
Review Type	Evidence-based narrative review	-	Framework for evidence synthesis
Databases Searched	PubMed, Scopus, Web of Science, Google Scholar	-	Comprehensive literature coverage
Publication Period	2020–2026	-	Captures recent technological developments
Search Keywords	Maxillofacial reconstruction, 3D printing, patient-specific implants, CAD, virtual surgical planning, bioprinting	-	Broad yet targeted retrieval strategy
Study Types Included	Original research, clinical studies, systematic reviews, meta-analyses, translational reports	Level I-V	High to Moderate
Language Restriction	English	-	Moderate
Exclusion Criteria	Non-English articles, conference abstracts, studies with insufficient methodological details	-	Improves methodological consistency
Evidence Evaluation	Relevance, methodological rigor, clinical applicability, and translational significance	Levels I–V	High
Primary Focus Areas	Digital workflow, implant design, biomaterials, surgical outcomes, translational challenges	Levels II–V	Moderate to High
Outcome of Synthesis	Identification of current advances, limitations, and future directions in personalized maxillofacial reconstruction	Synthesized across Levels I–V	Overall High
Systematic Reviews and Meta-analyses	Quantitative synthesis of clinical outcomes and technology performance	Level I	Very High
Prospective Clinical Studies	Evaluation of patient-specific implants and surgical outcomes	Level II	High
Retrospective Clinical Studies	Assessment of reconstructive outcomes and complication rates	Level III	Moderate
Experimental and Preclinical Studies	Investigation of biomaterials, manufacturing processes, and biomechanical performance	Level IV	Moderate
Expert Opinions and Technical Reports	Emerging concepts, workflow optimization, and future perspectives	Level V	Low to Moderate

peratures through a heated extrusion nozzle. While it does have lower surface finish and accuracy than Stereolithography (SLA), FDM provides an affordable means of creating instructional models, creating inexpensive surgical tooling and designing rapid prototypes [29].

Direct Metal Laser Sintering (DMLS) / Electron Beam Melting (EBM): Metal additive manufacturing techniques, particularly titanium alloys, provide highly dense, highly durable implants at the forefront of technology. These techniques enable complex craniofacial and maxillofacial reconstructions because of the ability to create precise lattice geometries, porous bioactive surfaces, and custom load-bearing devices with high mechanical reliability [30,31].

Digital workflow for personalized maxillofacial reconstruction

To prepare for customized maxillofacial reconstruction based on clinical/traditional practices, the first step is obtaining anatomical information by high-resolution CT/MRI scans of the victim's body. After importing that scan data into a computer program, software programs will allow you to create 3-dimensional (3D) images of the patient's anatomy to include all relevant anatomical structures (e.g., active tissue, bones) from the scan. The CAD tools associated with these models allow for virtual surgical planning, including defect assessment, implant customization, mirroring of the unaffected side of the face, and design of the surgical guide. After finalizing these components via CAD model development, the components may be manufactured using 3D printing. To ensure safe implanting and use in surgery, all printed devices undergo cleaning and post-curing/heat treatment, surface finishing, sterilization, and extensive quality inspection [32-34].

Biomaterials for Personalized Maxillofacial Implants

Material choice is a key aspect of successful reconstruction of the maxillofacial region. Maxillofacial implants must be able to meet all four requirements of mechanical strength, biological compatibility, radiographic performance, and manufacturability. A proper balance of these requirements results in long-term stability, successful function, and good long-term clinical results [35, 36].

Titanium and titanium alloys

Titanium continues to be the most popular material for use in craniofacial implants because it has an excellent strength-to-weight ratio, good overall corrosion resistance, good long-term fatigue resistance, and high biocompatibility as a material [37]. The naturally occurring stable oxide layer that develops on the surface of the titanium allows for strong bonding of bones to the implant. Furthermore, with the advent of additive printing, it is now feasible to print titanium implants with porous lattice designs that allow for bone to infiltrate into the implant, improve biological fixation, and reduce the mismatch of mechanical stiffness of the implant and surrounding native bone [38,39].

Polyetheretherketone (PEEK)

PEEK is an emerging material for patient-specific maxillofacial repair, thanks largely to its high-performance characteristics as a thermoplastic. With an elastic modulus comparable to that of cortical bone, PEEK would appear to reduce stress shielding and increase load transfer [40,41].

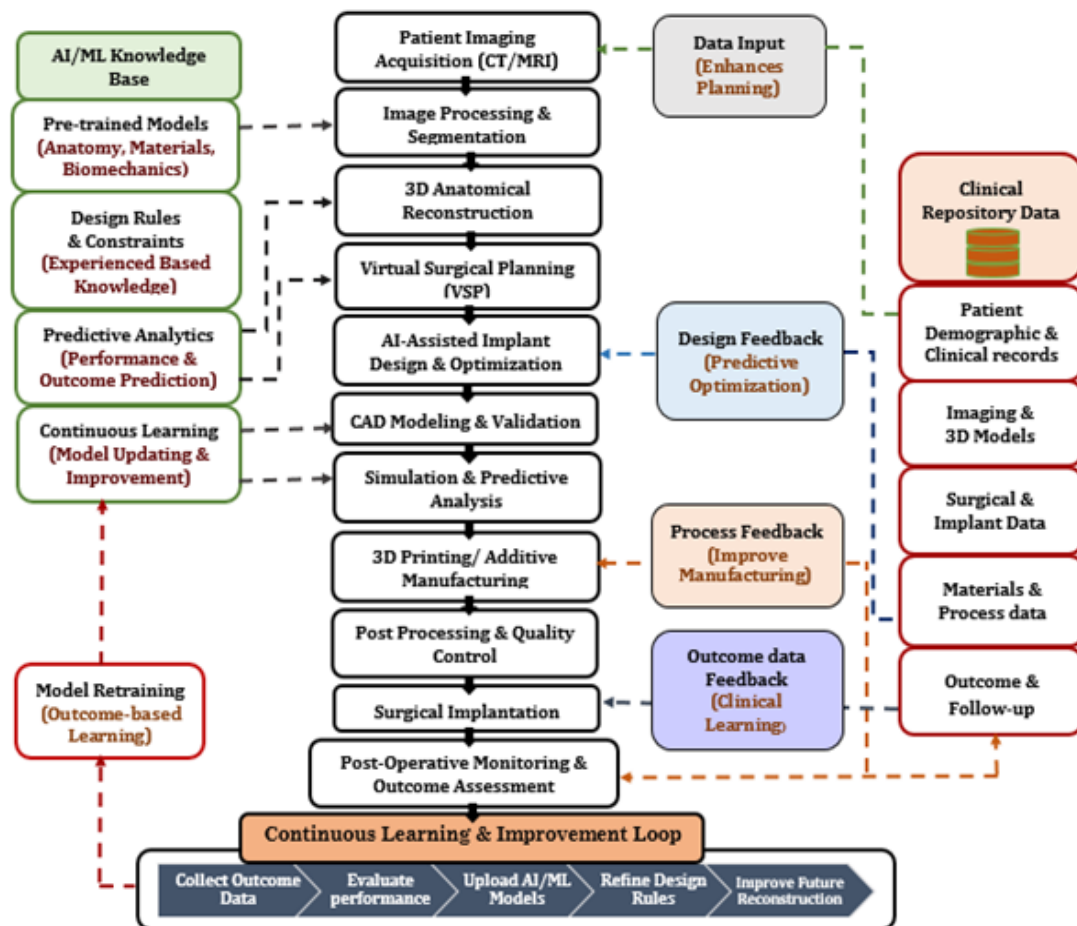


Figure 1: Digital workflow for personalized maxillofacial reconstruction with AI/ML integration and continuous feedback loops

Additionally, the use of PEEK also allows for more accurate postoperative imaging because PEEK is radiolucent and allows for fewer artefacts on imaging. PEEK is also chemically stable and lightweight. Native PEEK has a biological inert state; there are thus a wide variety of surface texturing and bioactive coatings currently under development as well as composite reinforcement technologies that will be utilized to help enhance osseointegration and achieve long-term fixation [42,43].

Bioactive ceramics

Hydroxyapatite, beta-tricalcium phosphate and calcium phosphate ceramics are excellent biomaterials because they have very similar mineral compositions to natural bone and exhibit excellent osteoconductivity. They are great for restoring non-weight bearing craniofacial deformities as well as for scaffold-based bone regeneration. They are also useful as a means to promote new bone formation and cellular attachment to existing bone [44-46]. These ceramics will have limited applications in high-load areas due to their inherent brittleness unless they are either strengthened or combined with other stronger comparable materials.

Biodegradable polymers

PLLA, PGA, and PLGA are examples of biodegradable polymers that may be used for both scaffolds in tissue engineering and as temporary fixation devices. These materials will gradually degenerate in the body as new tissue grows around them, which eliminates some or all of the need for additional procedures to remove implanted materials [47,48]. Additionally, their resorption behaviour makes them well suited for paediatric and regenerative applications. Nevertheless, in order to achieve long term clinical success, we must exercise very careful control over degradation rate, mechanical strength retention and biocompatibility of the degradation products in the body [49].

Composite materials

Composite systems combine multiple material categories to improve overall functionality and create materials with higher performance capabilities [50]. Examples of these composites include hybrid metal/polymer implants, polymer/ceramic scaffolds, and PEEK reinforced with hydroxyapatite. The mechanical properties of each of these composite materials provide superior mechanical performance, enhance the odds of osseointegration, and offer enhanced processing characteristics through their integrated properties of strength, toughness, and biological activity [51,52]. This increased interest in the use of multifunctional devices in advanced maxillofacial reconstruction is being fueled by on-

going research on the limitations of using single-material implants.

One optimal way to improve the bioactivity of PEEK is using dual-layer coatings comprising antimicrobial peptide/hydroxyapatite (AMP/HA). Coating PEEK with AMP/HA can only occur after activation of its otherwise bioinert surface. Common methods of activating the surface of PEEK include plasma treatment, sulfonation or chemical etching, and generating sufficient quantities of reactive functional groups for enhancing coating adhesion [53]. The HA layer provides an osteoconductive interface for bone cell attachment and mineralization, and antimicrobial peptide is subsequently attached to provide antibacterial features [54]. In order to prevent interfacial delamination, interfacial engineering techniques are used, including surface roughening, chemical bonding and functionally graded coating architectures which improve mechanical interlocking and decrease stress concentrations [55]. Additionally, these interfacial engineering approaches provide improved coating stability, osseointegration and long-term performance of the PEEK composite biomaterials, therefore making these biomaterials good candidates for advanced maxillofacial reconstruction [56].

Bioinks for bioprinting

Hydrogels, collagen, fibrin and other biocompatible materials with added stem cells are now used as 'bioinks' for bio-scaffold manufacture. This is a way to create scaffolds that allow for cellular proliferation, differentiation and regeneration of tissue, resulting in 'living' implants that will contribute to the production of fully functional tissues [57, 58]. These bioinks have been successful in numerous experimental studies with both soft tissue and bone regeneration and have the ability to dramatically change the way maxillofacial repairs are completed [59].

Because there is no one single biomaterial that can meet every medical need, there are many types of biomaterials that are used for reconstruction and repair throughout the craniofacial and maxillofacial regions. The properties of a material will determine the suitability of any bioengineered implant in terms of the strength, biocompatibility and/or compatibility for imaging, degradation characteristics, weight, and functional requirements of the application. Osseointegration and strength are provided by titanium; PEEK provides flexibility and imaging; ceramics provide osteogenicity; biodegradable polymers allow for temporary repair; composite biomaterials allow for multifunctionality and bioinks are used in tissue engineering [60, 61]. The main characteristics, advantages, disadvantages and application of these materials are presented in table 2.

Table 2: Comparative analysis of biomaterials used in craniofacial and maxillofacial reconstruction [62]

Types of Materials	Mechanical and Structural Properties			Key Advantages	Major Disadvantages	Application
	Elastic Modulus (GPa)	Tensile Strength (MPa)	Typical Porosity (%)			
Titanium & Titanium Alloys	110-115	900-1100	30-80% (lattice structures)	High-strength, osseointegrative material for load-bearing use.	Stress shielding and imaging artifacts.	Mandibular and cranial implants
PEEK	3-4	90-100	<10%	Lightweight, radiolucent, bone-mimetic thermoplastic for patient-specific implants.	Limited osseointegration without surface modification.	Cranial and orbital implants
Bioactive Ceramics	5-120	10-100	40-80%	Osteoconductive material for bone repair and regeneration.	Brittle with limited load-bearing capacity.	Bone defect fillers
Biodegradable Polymers	1-7	30-100	40-90%	Resorbable material for temporary fixation and tissue regeneration.	Limited durability; requires controlled biodegradation.	Bone scaffolds
Composite Materials	5-50	100-300	20-70%	Multiphase material with enhanced strength and osseointegration.	Complex fabrication, interfacial instability, and high cost.	Temporary fixation devices
Bioinks for Bioprinting	0.001-0.1	0.01-1	80-99%	Cell-laden bioink for tissue regeneration.	Experimental stage with regulatory and mechanical limitations.	Advanced patient-specific implants

Role of 3D Printing in Maxillofacial Reconstruction

Maxillofacial reconstruction is experiencing a shift from traditional methods to a new methodology for diagnosis, surgical planning and therapy due to 3D printing technologies. The transformation of medical imaging into three-dimensional physical objects allows doctors to manufacture patient specific models, surgical guides and implants [63, 64]. Bridging the gap between digital planning and physical implementation, this guarantees remarkable levels of accuracy, customisation, and efficiency in intricate craniofacial management [65].

3D printing will overcome traditional challenges faced by maxillofacial reconstruction, like restoring facial symmetry, retaining structural integrity/function and providing an aesthetically pleasing result [66]. Surgeons can now design entire procedures using models as well as anticipate patient specific anatomical variations when designing/constructing devices that will integrate with each patient's anatomy [67].

Integrating patient-specific and virtual implants with additive manufacturing workflows has led to fewer than 2 mm of reconstructive accuracy errors, based on recent clinical studies [68]. Meta-analyses of comparative studies between traditional reconstruction techniques and customized reconstructions have shown between 15% and 35% reduced operating time; improved anatomic symmetry; and increased patient satisfaction with the final results [69]. These findings support the ongoing clinical development of additive manufacturing techniques for the provision of customized craniofacial implants.

With the help of 3D printing as part of clinical processes, the time spent in the operating room is reduced and surgical results are improved, among many things, patient satisfaction and empowerment. In current day, it continues to improve and promises to be the most fundamental component of personalised maxillofacial treatment that could have functional and aesthetic rehabilitation more accurate than previous standards. Includes preoperative planning wherein 3D models printed anatomically along with virtual surgical planning (VSP) aid in accurate surgical procedures. Custom implants, biocompatible materials as titanium like PEEK bioresorbable polymers or bio-printing, a novel frontier derived from living cells and bioactive scaffolds to regenerate soft tissue and bone are new [70,71].

a) Preoperative planning

Personalized maxillofacial reconstruction is contingent on accurate imaging, while high-resolution modalities like CT and MRI offer invaluable data on anatomy. Subsequently, these images are converted to DICOM files so that the soft tissue and bone structures can be separated with the help of segmentation software. The eventual 3D modelling takes place through the assist of CAD software for virtual surgical planning. Through VSP, the fractures, deformities, and anatomical asymmetries can be precisely perceived and examined, in turn allowing the surgeons to practice and emulate very difficult and delicate surgeries. The osteotomies, resections, and implant placements can be planned comfortably in this virtual setting to guarantee that the surgical team can have confidence, predict intraoperative challenges, and enhance teamwork communications. Customized 3D printed templates are created from the finalized surgical plan alongside drilling, positioning, and cutting guides. These instruments indeed enable ultra-precise surgical intervention in challenging cases, including those with trauma, oncological excision, or congenital deformity. It reduces the time of surgery and also improves accuracy [72-75].

b) Surgical guides and cutting templates

With the advent of 3D printing, cutting templates and surgical guides are being used to make fine adjustments in highly delicate surgeries. Such aids facilitate accurate osteotomies for the reconstructions of mandibles and maxillae, and they promote optimal bone alignment and maintain the integrity of the structures [76]. Not least, they also facilitate alignment of grafts and placement of implants, so that the error margin is narrow and surgical accuracy is increased. This leads to a drastic increase in patient-specific outcome results and optimises processes because the guides offer pre-planned surgical strategies for intraoperative reductions and time cuts [77].

c) Custom implants and patient-specific prosthetics

3D printing is now the most advanced technology for manufacturing patient-specific prosthetics and individually tailored implants for maxillofacial reconstruction procedures [78]. 3D printing, with computer-aided design (CAD) software, is using a stupendous amount of anatomical

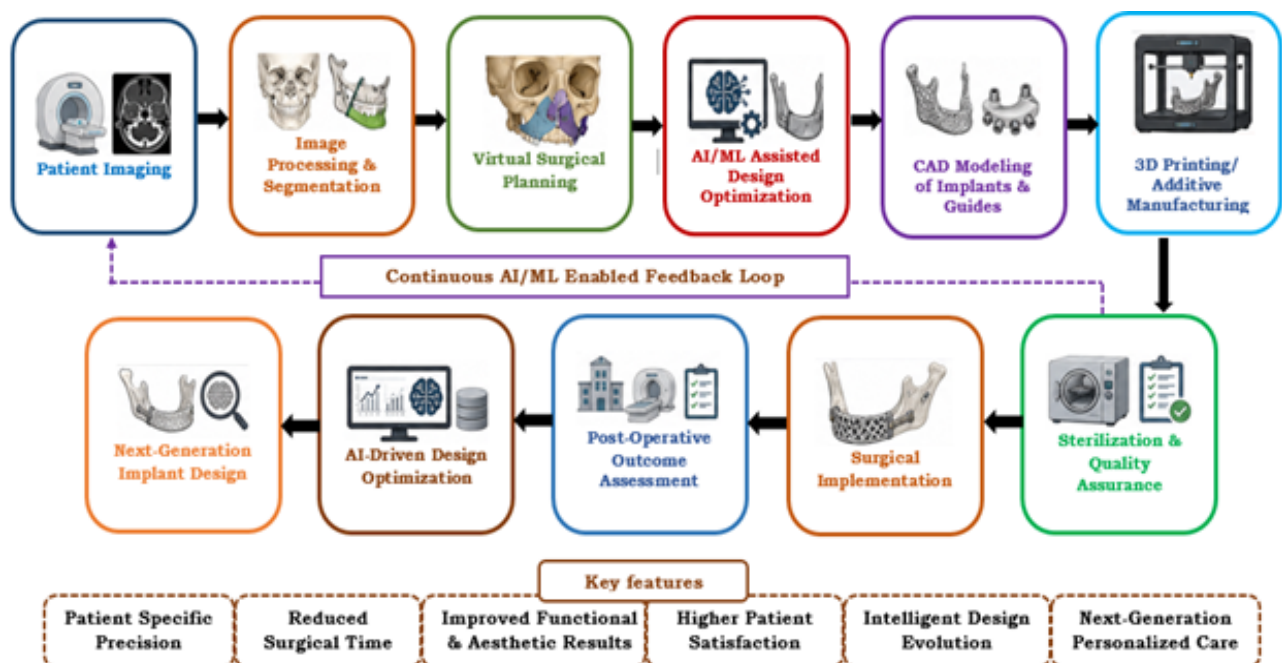


Figure 2: Role of 3D printing in maxillofacial reconstruction

data provided by very precise imaging modalities, such as CT and MRI, for the construction of implants suitable for the intended surgical delivery, facilitating their desired functionality and aesthetic outcomes germane to the patient's specific bone configuration [79]. Custom implants made from titanium, PEEK and other materials are often installed for correction of complex defects in the orbital floor, maxilla and mandible [80]. Whereas, PEEK is a light, radiolucent substitute with great mechanical properties; titanium, however, is a material with excellent strength and biocompatibility [81]. These custom implants shorten postoperative recovery times, lessen intraoperative modifications, and decrease surgery times [82].

Using prosthetics like orbital, nasal, and auricular prostheses customized for skin tone and facial features, human facial copies can also be created [83]. One advantage of the newer prostheses is that they fit better, appear better, and are, even more, comfortable than those made by traditional means, increasing the patient's self-esteem and life [84]. Another application is on customization of the 3D printing concepts: so that they maximize long-term outcomes in terms of healing and recovery [85]. Three-dimensional (3D) printing is a significant milestone in providing personalized medical treatment in maxillofacial care, enabling the production of personalized implants and prosthetics [86].

d) Bioprinting and tissue engineering for bone grafting and scaffolds

3D printing, as opposed to traditional methods of reconstruction, is evolving into two new technology categories, bioprinting and tissue engineering, both of which allow for the creation of scaffolding and bone grafts [87]. It is the biologically functional structures mimicking real bone that distinguish such methods from one another, enabling integration and regeneration of tissue [88]. Layer-by-layer deposition of bioinks consisting of living cells, growth hormones, and nanomaterials forms the basis for bioprinting gene-specific grafts for complex craniofacial anomalies [89]. Artificial bone scaffolds in craniofacial surgery are mere structures designed to facilitate cellular adhesion, proliferation, and new bone formation [90]. The scaffolds have been thus engineered to allow for porosity, morphology, and mechanical properties, which mimic those of the native bone, to enhance functional and aesthetic purposes. Com-

monly employed materials include biodegradable polymers and osteoconductive ceramics due to their ability to slow down resorption while the natural bone takes over [91].

Bioprinting has the potential to integrate vascular channels and biological signals which are needed for long-term viability and healing [92]. Thus, the tissue-engineered scaffolds as opposed to the conventional graft approaches can allow a faster recovery, prevent the necessity for intervention procedures, and minimize donor site morbidity [93]. Rapid advancements in 3D printing technology through bioprinting, stem cell research, and bioactive material have paved the way for 3D printing to become a major contributor to the delivery of personalized medical treatment and the restoration of maxillofacial skeletons [94].

Benefits and Limitations of 3D-Printed Personalized Implants

The installation of 3D printers has allowed surgeons performing maxillofacial reconstructions to make custom implants that correspond to each individual patient's unique anatomical structure, thus enhancing both surgical precision and improving clinical outcomes for patients who undergo these procedures [95]. However, there are certain concerns that ought to be answered before these implants can be utilized sufficiently in a clinical setting.

a) Benefits of 3D-printed custom implants

3D Printed custom implants provides better fit to an individual's anatomy, allowing for quicker surgical planning and shortened recovery. Besides improving both functionally and aesthetically, they also offer geometries that may not be created with traditional ways of producing implants and thus ensure all patient treatment is specific to each individual [96,97]. Additionally, because of their quick ability to be produced, custom implants will more easily integrate with the patient's bone tissue, also resulting in a quicker recovery after surgery [98].

i) Patient-Specific Design: 3D Printed custom implants can be produced from the individual's physiology by creating a digital representation from some form of imaging such as CT or MRI. This allows for a precise fit on the surgical site using custom-made plates [99,100].



Figure 3: Clinical benefits, clinical failure modes and risks, and translational challenges of 3D printed custom implant

ii) Improved Surgical Accuracy and Efficiency: By adding the benefit of using patient-specific implants, as well as 3D printed surgical templates and guides, there is greater precision when performing surgeries. This will result in a faster recovery time for patients due to less intra-operative complications and reduced time spent in the operation [101].

iii) Enhanced Biocompatibility and Osseointegration: Bioceramics, PEEK, and titanium have excellent biocompatibility and good bone integration along with modulus. Some implants also incorporate bioactive coatings to further enhance osseointegration and soft tissue attachment [102,103].

iv) Reduction in Postoperative Complications: These types of implants are 3D-printed, which means they can be produced to specification for each patient, resulting in significantly reduced chances of misalignment, elimination of the risk for additional implant failure, and a decreased likelihood for infection usually associated with generic pre-manufactured implants. They also reduce morbidity that usually comes with using tissue from the donor site, leading to a better quality of life of patients [104,105].

v) Versatility in Material Selection: There are many biomaterials, the applications of which could be linked with 3D printing. Implants that are ceramic and polymer-based kinds of materials bear non-load-bearing or aesthetics purposes, while implants for metals carry a load-bearing strength [106,107].

vi) Preoperative Planning and Simulation: Surgeons benefit from using VSP by improving their ability to make good decisions, decrease utility errors and promote team acculturation [108].

b) Clinical failure modes and long-term considerations

As there are still many clinical and material factors that impact long-term recovery, the recent advancements in 3D printing and patient specific implant technology have not eliminated these challenges [109, 110]. To improve durability, optimize implant design, and create specific treatment plans for each patient, it is important to understand the different pathways to potential failure [111,112].

i) Implant Exposure: Soft-tissue inadequacy, dehiscence, vascular insufficiency, and previous radiation therapy can all contribute to the exposure of an implant, which is a life-threatening complication [113, 114]. The risk of developing an infection and failing the implant becomes higher, and usually will require additional revision surgery [115]. As a result, careful planning and restoration of the soft tissue are critical.

ii) Bacterial Film Formation: There may be biofilm development on implant surfaces, particularly on porous titanium structures that are ideal for microbial attachment [116].

Once biofilms are present, they are difficult to remove, which can lead to long-term inflammation, chronic infection, poor healing, and ultimately removal of the device [117]. Advanced antimicrobial coatings and modifications to the implants are being examined to eliminate this problem.

iii) Stress Shielding: When an implant that is rigid is loaded above its tolerance level, stress shielding can occur which will decrease the amount of stress being transferred to the surrounding bone. There can also be a lack of bone density and potentially, implant failure [118, 119]. Maintaining normal load distribution is accomplished through use of optimized geometries/lattice structure.

iv) Mechanical Fatigue and Microfracture: Mechanical fatigue, micro-cracking, and eventually the breakage of patient-specific implants subject to repeated chewing forces applied to load-bearing regions can be attributed to the occurrence of repetitive loads. The ability of an implant to withstand repeated use will depend on the correct choice of materials and optimal design for achieving reliable mechanical function over time [120].

v) Poor Soft-Tissue Integration: Soft tissue integration is important to maxillofacial repair besides osseointegration [121]. Poor implant-tissue attachment can lead to inflammation and delayed healing, mucosal irritation, and exposure of the implant [122]. Creation of bioactive surface modifications would help to achieve good long-term clinical results related to soft tissue adhesion.

vi) Long Term material Degradation: Long-term degradation continues to be a concern for polymeric and coated implants even though they have excellent biocompatibility [123]. It is important to use durable

biomaterials and provide continuous clinical monitoring of implants because aging, wear, corrosion, hydrolysis and delamination of the coatings can negatively affect both biological performance and structural integrity [124].

c) Limitations of 3D-printed custom implants

The high cost of production, sometimes coupled with the restricted range of materials available and regulatory hurdles, happens to be some of the problems 3D-printed customized implants are faced with. Additionally, complex designs often require special tools and skills, frequently leading to very long lead times. Long-term data are currently sparse, with the mechanical properties not necessarily being representative of those obtained with conventional implants [125,126].

i) High Production Costs: When using VSP, experts will still face significant costs associated with software, specialized materials, and 3D printing technologies. In addition, advanced imaging techniques and manufacturing methods, used to produce custom-made implants, may not yet be found in all types of healthcare facilities [127,128].

ii) Regulatory and Approval Challenges: Strict regulation standards have to be met by custom implants to ensure their effective working and safe use. The long, arduous, and expensive process to carry out approval of patient-specific implants and innovative biomaterials may work as an impediment against their widespread adoption [129,130].

iii) Limited Availability of Bioprinting and Regenerative Materials: Fully functional live implants integrating with native tissues are still experimental, despite encouraging advances in bioprinting and tissue-engineered implants. The application of bioresorbable and regenerative materials clinically is still a very challenging affair [131,132].

iv) Need for Specialized Training: A successful 3D print application in maxillofacial reconstruction must be mastered by proficiency in additive manufacturing, computer-aided design, and medical imaging [133,134]. A lot of surgeons and medical staff would require further education to make use of this technology efficiently.

v) Potential for Material Degradation and Longevity Concerns: Additionally, researchers do not know how long titanium and polyether ether ketone (PEEK) would last, and how they would resist degradation and wear over time. This emphasizes the requirement for further research; particularly since polymers used in medicine right now may fail earlier than conventional materials [135,136].

vi) Ethical and Legal Considerations: The ethical and legal implications associated with the custom manufacturing of medical devices will also pose challenges for healthcare providers [137]. Specific issues include potential liability problems should a patient experience an adverse effect due to the implant, the confidentiality and integrity of the patient's personal information, as well as issues related to the ownership of industrial design patents and manufacturing methods that pertain to custom-manufactured equipment in the healthcare industry [138,139].

Future Directions

3D printing technology and custom implants could really change the game in maxillofacial reconstruction. Biocompatible materials combined with advanced production methods, along with patient-specific anatomy, allows us to produce precise, aesthetically pleasing end products that address the individual needs of each patient [140].

Bio-printing and tissue engineering

Bioprinting and Tissue Engineering for Global Bioprinting and Creation of Patient Specific Living Tissues for the Reconstruction of Maxillofacial Structures. The bioprinting (3D printing) process involves the layering of bioinks; suspension of cells, growth factors and biomaterials in generating complex tissue constructs that mimic the structure of soft tissues, cartilage and bone [141]. This versatile method enables precise anatomical customization producing superior functional and aesthetic results. Scaffolds are also created to cause cells to divide and regenerate in tissue engineering and will eventually become part of the patient's own tissues [142]. In particular, these technologies will be suited for the repair of maxillofacial tumor resections, trauma injuries, and congenital anomalies. Bioprinting allows for the fusion of biological and engineer-

ing principles to construct normal anatomical structures and concurrently interconnect those structures. The use of bioprinting may also produce lower rejection rates, faster healing, and longer-term regeneration than conventional grafts or synthetic implants currently utilized. Bioprinting and tissue engineering are in early stages of development, with continued advances in these techniques placing the future of personalized regenerative medicine at the forefront of maxillofacial surgery [143].

AI and machine learning in 3D implant design

The process of implant design continues to develop rapidly with advances in AI and ML technologies, which allow for the production of customized manufacturing solutions for each patient through 3D printing technology. These Data and Image-based (DI) implants are made using imaging (CT/MRI scans) of the patient. These data enable tailored implants that fit volumetrically [144]. Implant dimension, material selection, and mechanical properties can be optimized to guarantee enhanced durability and performance with ML methods. Other features are the reduction of development time and human error in automated design processes. It applies predictive analytics powered by AI for predicting surgical outcome to guide clinicians in making the best possible decision [145]. The AI software can also enhance the quality control by flagging design errors before production. Overall, integrating AI and ML into 3D implant design results in better outcomes for individual patients and more efficient design processes—such as models developed in-house for each patient. They also create a truly personalized way to develop surgical device [146].

Smart and bioactive implants

Smart and bioactive implants are a new material class in maxillofacial restoration actively encouraging healing and regeneration at restoration of structure. Smart implants can be designed with embedded sensors to monitor the status of any infection/healing (real-time) and respond to changes in body (chemical composition, temperature, or amount of mechanical stress) [147]. As a result, these bioactive implants will assist in reducing inflammation, increasing bone formation, and increasing osseointegration, thus assisting neighbouring tissues' actions in a synergistic manner. Growth factors, antibiotics, or calcium phosphates usually could be delivered or coating-borne these bioactive implants to promote their integration into the tissues. The combination reduces complications, increases long-term success, and gives enhanced healing outcomes via bioactivity and smart functioning. These new technologies have great promise for the maxillofacial surgeon in providing customized, responsive, and regenerative solutions as the field advances [148].

4D bioprinting

Another advanced technology used to produce maxillofacial implants is 4D bioprinting. This process allows for the modification of an implant's size, shape, and/or function and is based on different physical properties of the body (Temperature, pH level, and amount of moisture) [149]. The ability to design tailored implants utilizing intelligent biomaterials to correct skeletal discrepancies of the jaw and face will provide additional benefits to patients. In comparison with traditional implants, these adaptive devices will lead to improved tissue integration, healing, and fit. Such devices will be particularly beneficial for young patients and for use in complex reconstructions [150]. 4D bioprinting has great promise for future applications in both regenerative medicine and maxillofacial surgery even though it is still in its infancy [151].

Limitations of the Present Review

While this manuscript provides an excellent overview of the progress made recently in developing customized maxillofacial reconstructions, it has some limitations. There is a significant publication bias due to the greater probability of positive outcome studies being published versus studies with negative or inconclusive findings, leading to an underestimation of implant exposure, bacterial colonization, stress shielding, and material degradation late in the course of use.

There are also significant disparities in the quality of the literature available today; there are case reports, predictive-care studies, retrospective research, and systematic review articles—and therefore direct comparisons of different manufacturers and types of implant materials are made difficult if not impossible.

Another hindrance to widespread adoption of these advanced technologies is the degree of economic and geographic disparity across different regions of the world. In developed nations with abundant resources, it is still far more feasible for hospitals or healthcare systems to implement advanced imaging systems, virtual surgical planning software, additive manufacturing centres, and regulatory pathways than it is for developing nations.

For this reason, further research focusing on multicentre randomised trials, standardised reporting requirements, long-term clinical monitoring and cost-effectiveness assessment, as well as harmonised regulatory frameworks will be crucial if we are to facilitate continued global clinical translation.

Conclusion

With the availability of 3D printing technology for the realms of maxillofacial reconstruction, accurate patient-dependent tools have been developed which led to enhanced surgical outcomes. The surgeon can rely on the 3D printing of patient-specific surgical instruments and implants to give him confidence and accuracy regarding navigation during difficult interventions. Custom implants improve functional and aesthetic repair, ease recovery, and shorten operative time when engineered to complement the anatomy of the individual patient. The bulk of work today is carrying out preoperative planning and custom cutting implants of materials like titanium and PEEK, but there are more groundbreaking technologies on the horizon. Engineering technologies like bioprinting, regenerative scaffolds, and smart materials further erode the dividing line between biology and engineering in the near future for tissue regeneration and live implants. Meanwhile, CAD, bioprinting, and intelligent implants are set to affect the future phenomenally despite economic challenges and regulatory and material hurdles. Further research needs to work alongside collaboration from the surgeon, engineer, or material scientist for the full potential manifestation of this technology. Certainly, 3D printing will take a centre stage in personalized maxillofacial surgery as the field advances, not only transforming smiles but reconstructive care itself.

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