

Application of Rapid Prototyping Techniques in Customized Maxillary Implants for Mucormycosis-Induced Defects: A Comprehensive Review

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Abstract- During the COVID-19 pandemic, a serious fungal infection called Mucormycosis began affecting many patients, especially those with weakened immune systems recovering from prolonged COVID-19 treatment. This infection commonly damages the maxilla (upper jaw), often requiring surgical removal of infected bones such as the upper jaw, lower jaw, and cheekbone. As a result, patients face challenges in eating, speaking, and facial appearance. Rapid Prototyping (RP) offers a promising solution for these cases by enabling the development of patient-specific metallic implants. These customized implants can be designed from medical scan data and fabricated quickly to replace the removed bone structures. This review highlights the role of RP in the medical field, particularly in designing and producing implants for patients suffering from Mucormycosis. The use of RP improves treatment planning, enhances surgical precision, and reduces recovery time, offering hope for better rehabilitation outcomes.

Key Words: Mucormycosis, Maxilla, Customized Implants, Rapid Prototyping, Medical Reconstruction, COVID-19.

1. INTRODUCTION

The COVID-19 pandemic brought with it not only a viral crisis but also a surge in opportunistic infections, among which mucormycosis emerged as a particularly aggressive and life-threatening condition. This invasive fungal disease, often affecting immunocompromised patients, found a fertile ground in post-COVID individuals especially those subjected to prolonged steroid therapy and oxygen support. Among the most devastating complications of mucormycosis is its impact on the maxillofacial region, particularly the maxilla, which plays a vital role in facial integrity, speech, mastication, and aesthetics. As surgical debridement remains the primary life-saving intervention, the resulting structural deformities pose complex reconstructive challenges. Traditional methods of rehabilitation have proven inadequate in many such cases, thereby highlighting the growing need for innovative, patient-specific solutions. This review attempts to critically examine the clinical impact of mucormycosis on the maxilla, evaluate the limitations of conventional reconstruction techniques, emphasize the need for personalized implants, and establish the importance of continued research in this field.

1.1 Clinical Impact of Mucormycosis on the Maxilla

Mucormycosis, commonly referred to as “black fungus,” is a rare but highly aggressive fungal infection caused by mucormycetes. Its clinical relevance surged dramatically during the COVID-19 pandemic, particularly among immunocompromised patients and those undergoing steroid therapy. Among the various craniofacial structures affected, the maxilla is particularly vulnerable due to its vascular architecture and proximity to the paranasal sinuses common entry points for fungal spores.

The clinical manifestations of mucormycosis involving the maxilla are severe and disfiguring. The infection typically originates in the nasal or oral cavity and can rapidly invade the maxillary sinus, palate, alveolar bone, and orbit. This can lead to palatal perforation, loss of maxillary dentition, oroantral fistulas, and in severe cases, necrosis of facial structures. The loss of the maxilla significantly impairs critical functions such as mastication, speech, deglutition, and facial aesthetics. Additionally, patients may experience facial swelling, nasal blockage, purulent discharge, and in advanced stages, orbital cellulitis or blindness. These outcomes are not only physically debilitating but also psychologically traumatizing for patients.

Given the urgency and aggression of mucormycosis, especially in post-COVID cases, early diagnosis and radical surgical debridement become crucial. However, surgical excision, while life-saving, often leaves patients with extensive midfacial defects. These require complex, multidisciplinary rehabilitation involving maxillofacial surgeons, prosthodontists, ENT specialists, and sometimes neurosurgeons. The reconstructive challenge lies in restoring not only anatomical form but also the functional and aesthetic integrity of the midface.

1.2 Limitations of Traditional Reconstruction Techniques

Traditional techniques for maxillary reconstruction, including obturators, autologous bone grafts, and regional or free flaps, have been the standard approach for decades. However, each of these methods presents significant limitations, especially when addressing complex defects resulting from mucormycosis. Obturators, often used as a prosthetic substitute for missing maxillary structures, provide temporary closure of oroantral communications. However, they do not restore bony anatomy or soft tissue contour. Obturators can also be uncomfortable, unstable during function, and often lead to compromised speech and mastication. Autologous bone grafting from sites like the iliac

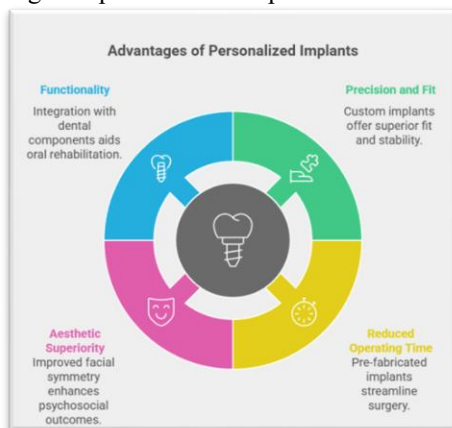
crest or fibula has been employed for bony reconstruction. However, these procedures are invasive, require multiple surgeries, and carry a risk of donor site morbidity. Moreover, achieving perfect anatomical symmetry and integration remains a challenge due to limitations in manual shaping of grafts. Microvascular free flaps, such as fibula or radial forearm flaps, have emerged as more robust options for extensive reconstruction. They allow simultaneous reconstruction of soft tissue and bone and have high success rates.

1.3 Rise in Need for Personalized/Custom Implants

The limitations of conventional methods have paved the way for a paradigm shift towards patient-specific, computer-aided design and computer-aided manufacturing (CAD/CAM) based solutions. Personalized or custom-made implants represent a new frontier in maxillofacial reconstruction that addresses the inherent challenges of traditional techniques.

The use of 3D imaging, such as cone beam computed tomography (CBCT), allows for precise visualization of craniofacial defects. With the help of CAD/CAM software, implants can be virtually designed to match the exact anatomical contour of the patient's maxilla. These implants, typically fabricated from biocompatible materials such as titanium or polyetheretherketone (PEEK), are tailored to restore symmetry, aesthetics, and functional load-bearing capabilities.

The advantages of personalized implants are multifold:



In post-mucormycosis cases, where surrounding soft tissue is often compromised and revascularization is uncertain, the use of such implants becomes even more critical. They offer a non-biological, infection-resistant solution that does not rely on donor site morbidity or vascularized graft uptake. Furthermore, 3D printing technology allows rapid prototyping and production, enabling quicker turnaround for urgent reconstructions an essential aspect in managing post-infective facial destruction.

1.4 Justification for the Importance of This Review

This review is both timely and significant for several reasons. First, the COVID-19 pandemic highlighted mucormycosis as an emerging public health concern, especially in countries like India where its incidence rose alarmingly among post-COVID patients. The maxillary destruction caused by this opportunistic infection presents new challenges in craniofacial reconstruction, necessitating an updated understanding of treatment modalities.

Second, existing literature on maxillofacial reconstruction largely revolves around trauma or oncological

resections. There remains a critical gap in focused studies that specifically address post-mucormycosis maxillary defects and their optimal rehabilitation pathways. This review bridges that gap by contextualizing the unique challenges posed by fungal necrosis, such as irregular defect margins, poor tissue vascularity, and immunocompromised patient conditions.

Third, this review promotes awareness and dissemination of advanced reconstructive technologies such as CAD/CAM and patient-specific implants. While these technologies have been around, their adoption in resource-constrained settings remains limited due to cost and technical barriers. By compiling existing evidence, this review advocates for broader clinical integration of personalized implant solutions that offer better outcomes in terms of form, function, and aesthetics.

Additionally, this review serves an educational function for practitioners across disciplines oral surgeons, prosthodontists, ENT surgeons, and biomedical engineers emphasizing the need for interdisciplinary collaboration. As reconstruction after mucormycosis is not solely a surgical challenge but also a prosthetic, functional, and psychological concern, the review underlines the importance of holistic rehabilitation strategies.

Lastly, this review is justified from a policy and systems-level perspective. With growing emphasis on digitization and 3D printing in healthcare, there is a need for evidence-based policy frameworks that support cost-effective integration of personalized implants into mainstream clinical practice, especially in high-burden public hospitals. The insights provided in this review can influence future guidelines and standard operating procedures in oral and maxillofacial reconstruction.

2. BIOMEDICAL ADVANCEMENTS

Other important applications of the prototyping technology are in the development of medical devices and instrumentations. Medical instruments that have been upgraded using the 3D technology include surgical fasteners, scalpels, retractors, display systems, among many others. Besides the designing of the medical devices, the prototyping technology is also used in the manufacturing of these devices. Devices that need to be specifically individualized for a particular patient are the candidates of the additive technologies.

Most hearing aid devices are designed using the stereolithography or the selective laser sintering. Other areas that are adapting the rapid prototyping technology are the replacement of teeth.

Some drug dosage forms are also designed by the use of these technologies. Especially the dosage forms those are difficult to design using any other method.

Tablets having a sustained drug release are also being manufacture using the rapid prototyping technology. The new technology has improved the safety of drugs to patients by minimizing the adverse drug reactions that may arise.

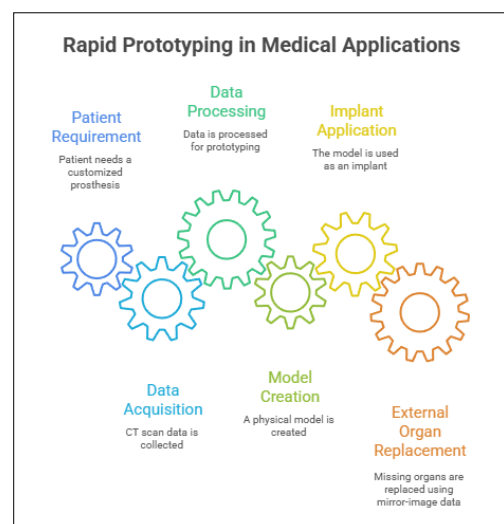
Application in the Manufacture of Prostheses and Implants:

Rapid prototyping plays a crucial role when it comes to implantations and use of prostheses. Through the technology, prostheses that have been specifically designed for a particular patient are now available. Patients whose requirement is

outside the standard size or those who require special treatments can now get some customized prostheses that fits them at an affordable cost.

Rapid prototyping and computed tomography technologies utilize techniques, such as X-rays and NMRI, and enable the transfer of data generated to be used as the input data for the rapid prototyping process. A lot of developments have been done to enhance the accuracy, interpretation, and the translation of the CT scan results. The accuracy of the models generated from the rapid prototyping systems have also been improved over time. Various types of rapid prototyping technology have been applied in the various medical uses with some of them being selected as the standard method. An example of standard method used for medical purposes is the CT scan used in the hip replacement surgical procedure. Data from the CT scan is combined with engineering data to join to the bone. The data is then turned into a plastic model to be applied as an implant for the patient.

Other medical application of the prototyping technologies is in the replacement of the external missing organs. In such instances, the remaining organ is scanned into a three-dimensional image, and the mirror-image of the data acquired is used to build data for the missing organ.



3. REVIEW OF LITERATURE

Methodology of Literature Collection

To ensure a comprehensive understanding of the current advancements in the field of maxillofacial reconstruction using patient-specific implants, an extensive literature search was conducted across several reputed scientific databases, including Scopus, PubMed, Web of Science, ScienceDirect, and IEEE Xplore. The search was limited to peer-reviewed articles published primarily between 2000 and 2022, with particular focus on studies from 2020 to 2022 to reflect recent developments and pandemic-related implications. A set of targeted keywords was used during the search process, including: “patient-specific implant,” “maxillofacial reconstruction,” “mucormycosis maxilla,” “customized titanium implants,” “3D printing in craniofacial surgery,” “computer-aided surgical planning,” and “CAD/CAM in reconstructive surgery.”

The inclusion criteria involved studies that specifically focused on the application of digital technologies, customized implants, and clinical outcomes in maxillofacial surgeries, particularly in cases involving bone loss due to infection, trauma, or tumor resection. Studies that provided clinical case results, discussed surgical techniques, or involved technological development in medical device fabrication were also considered. Conversely, papers that were outdated, unrelated to the maxillofacial region, or lacking technical or clinical relevance were excluded.

In total, around 40 research papers were reviewed in-depth. These were systematically categorized thematically into key focus areas: (1) imaging and data acquisition, (2) CAD/CAM design of implants, (3) rapid prototyping and materials used, and (4) clinical applications and outcomes. This thematic approach allowed for a clear synthesis of how each technological advancement contributed to solving specific clinical challenges, particularly in the context of mucormycosis-related maxillary defects.

Vijay Kumar Meena, et al.^[1] had designed and developed a patient-specific implant for the zygomatic area of a patient suffering from mucormycosis (fungal infection). He described how integration of computer-aided design (CAD) and 3D printing can be successfully used for developing custom implants for the sites for which readymade optimal solutions are not available. The CT scan data of the patient were used for the generation of a 3D model. The healthy side of the skull was mirrored and copied on the infected part, which served as a base for designing the implant. The prototype of the implant was printed using fused deposition modelling before finally printing in Ti6Al4V alloy using direct metal laser sintering process. The custom-designed implant fitted well to the patient’s skull during surgery. Proper facial aesthetics were maintained post-surgery. The work describes the application of CAD-based image processing software and additive manufacturing in the development of a custom implant for the sites for which no readymade optimal solution is available.

Mohammad Qasim Shaikh, et al.^[2] in their study, had investigated the feasibility of metal fused filament fabrication (MF3) to manufacture patient-specific maxillofacial implants. They reported design and fabrication of a maxillofacial implant prototype in Ti-6Al-4V using MF3 for the first time. The cone-beam computed tomography (CBCT) image data of the patient’s oral anatomy was digitally processed to design a 3D CAD model of the hard tissue and fabricate a physical model by stereolithography (SLA). Using the digital and physical models, bone loss condition was analyzed, and a maxillofacial implant initial design was identified. Three-dimensional (3D) CAD models of the implant prototypes were designed that matched the patient’s anatomy and dental implant requirement. In this preliminary stage, the CAD models of the prototypes were designed in a simplified form. MF3 printing of the prototypes was simulated to investigate potential deformation and residual stresses. The patient-specific implant prototypes were fabricated by MF3 printing followed by debinding and sintering using a support structure for the first time. MF3 printed green part dimensions fairly matched with simulation prediction. Sintered parts were characterized for surface integrity after cutting the support structures off. An overall $18 \pm 2\%$ shrinkage was observed in

the sintered parts relative to the green parts. A relative density of $81 \pm 4\%$ indicated 19% total porosity including 11% open interconnected porosity in the sintered parts, which would favor bone healing and high osteointegration in the metallic implants. The surface roughness of Ra: $18 \pm 5 \mu\text{m}$ and a Rockwell hardness of $6.5 \pm 0.8 \text{ HRC}$ were observed.

Alessandro Cucchi, et al. ^[3] aimed their study to evaluate the effectiveness/reliability of implant-prosthetic rehabilitations with the help of CAD/CAM customized titanium meshes technique in a consecutive series of cases. Ten patients in need of bone augmentation before implant therapy were treated using CAD/CAM customized titanium meshes. A digital workflow was adopted to design virtual meshes on 3D bone models. Then, Direct Metal Laser Sintering (DMLS) technology was used to produce the titanium meshes, and vertical ridge augmentation was performed according to an established surgical protocol. Surgical complications, healing complications, vertical bone gain (VBG), planned bone volume (PBV), lacking bone volume (LBV), regenerated bone volume (RBV), average regeneration rate (RR) and implant success rate were evaluated. All augmented sites were successfully restored with definitive implant-supported fixed partial dentures. Measurements showed an average VBG of $4.5 \pm 1.8 \text{ mm}$ at surgical re-entry. Surgical and healing complications occurred in 30% and 10% of cases, respectively. Mean values of PBV, LBV, and RBV were 984, 92, and 892 mm^3 , respectively. The average RR achieved was 89%. All 26 implants were successfully in function after 1 year of follow-up. This study suggested that the bone augmentation by means of DMLS custom-made titanium meshes can be considered a reliable and effective technique in restoring vertical bone defects.

Anamika Pandey, et al. ^[4] discussed the possible projected areas of implants in the human body and focused on human anatomy and its load-bearing capacity for designing any derailed organ with implants. Besides, they also discussed the different biocompatible materials and overall superiority of titanium-based bio-implants in terms of corrosion resistance, osteolysis, tribology, etc. Overall, they made an attempt to give a brief insight related to causes of dysfunctional bones, remedies to use bio-implants, processing through additive manufacturing and its further possibilities to bring out the most favorable and superior biocompatible implant.

Sandeep W. Dahake, et al. ^[5] aimed to find the usefulness of the customized surgical osteotomy guide (CSOG) for accurate mandibular tumor resection for boosting the accuracy of prefabricated customized implant fixation in mandibular reconstructions. In all, 30 diseased mandibular RP models (biomodels) were allocated for the study (15 for the experimental group and 15 for the control group). In the experimental group, CSOGs were used for accurate tumor resections, while in the control group, only preoperative virtual surgical planning (VSP) and reconstructed RP mandible model were used for reference. In both groups, preoperative mandibular reconstructions data were superimposed onto the preoperative VSP by registering images with the non-surgical side of the mandible. 3D measurements were taken on the reconstructed side and compared with the preoperative VSP and postoperative reconstructed mandible data. The sum of differences between

pre and postoperative data was considered the total error. The results showed that using CSOGs resulted in smaller total error, justifying their use over freehand tumor resection methods.

Mauro Cerea, et al. ^[6] studied and presented a digital technique for the fabrication of custom-made subperiosteal implants and reported on the survival and complication rates when using these fixtures. The retrospective clinical study data were gathered from five different private dental practices. Patients over the age of 60 treated with custom-made DMLS (Direct Metal Laser Sintering) titanium subperiosteal implants and restored with fixed restorations during a two-year period were included. After 2 years of follow-up, 67 out of 70 implants survived, giving a survival rate of 95.8%. Four patients reported minor postoperative issues, and the overall biologic complication rate was low (1.4%). Prosthetic complications occurred in 8.9% of the cases. The study concluded that, despite the limited sample and follow-up, DMLS titanium subperiosteal implants showed promising survival rates and minimal complications.

Emad Abouel Nasr, et al. ^[7] addressed the challenges in reconstructing mandibular defects following severe trauma. The study emphasized the mandible's vital role in essential functions like mastication and speech. The authors showcased the use of CT and MRI imaging, CAD, and additive manufacturing (AM) to design geometric models for customized implants. Electron Beam Melting (EBM) was used to fabricate these implants. The project demonstrated that it is now possible to design patient-specific implants accurately and apply them effectively using modern imaging and manufacturing techniques.

Jiankang He, et al. ^[8] introduced a method for designing a hemi-knee joint substitute made from titanium alloy and porous bioceramics using rapid prototyping (RP) and rapid tooling (RT) techniques. The femur bone model was reconstructed using CT images, and the implants were created with microporous features ($250\text{--}300 \mu\text{m}$). The assembled composite substitute was tested in vivo, and the results showed excellent anatomical fit and mechanical strength. The technique demonstrated the usefulness of RP in producing tissue-engineered implants and suggested its capability for other biomaterial-based substitutes.

Francesco Grecchi, et al. ^[9] demonstrated the use of Direct Laser Metal Sintering (DLMS) to fabricate a custom-made titanium mandibular implant for a 67-year-old female with squamous cell carcinoma. Traditional reconstruction methods had failed in this case. A digital workflow was used to design the prosthesis that replaced the mandible and supported a dental prosthesis. The procedure successfully restored the patient's masticatory function, showcasing DLMS as a reliable method for complex oral and maxillofacial reconstructions.

Aaron Vance, et al. ^[10] developed a Ti6Al4V tibial implant for Segmental Bone Defect (SBD) repair with stiffness matching to avoid stress shielding. Using μCT scan data, a digital bio-model was created, and the implant was designed with a sheathed periodic unit cell. Finite Element Analysis (FEA) predicted the implant's performance, which was validated by compression testing. The implant showed slightly

lower stiffness than native bone, favoring osseointegration. Surface roughness was also suitable for bone cell attachment. This research proposed a structurally optimized DMLS-manufactured implant for better integration.

Jovani Castelan, et. al. (2014)^[11] Their work aimed to pre-operatively manufacture custom-made low-cost implants and physical models ('bio models') of fractured skulls. The pre-operative manufacturing of bio models and implants allows physicians to study and plan surgery with a greater possibility of achieving the expected result. Customization contributes to both the esthetic and functional outcome of the implant because it considers the anatomy of each patient, while the low cost allows a greater number of people to potentially benefit. From CT images of a fractured skull, a CAD model of the skull (bio model) and a restorative implant were constructed digitally. The bio model was then physically constructed with 3D Printing, and Incremental Sheet Forming (ISF) was used to manufacture the implant from a sheet of pure grade 2 titanium. Before cutting the implant's final shape from a pre-formed sheet, heat treatment was performed to avoid deformations caused by residual stresses generated during the ISF process. A comparison of the dimensions of the implant and its respective CAD bio model revealed geometric discrepancies that can affect both functional and aesthetic efficiency. Nevertheless, the final shape preserved symmetry between the right and left sides of the skull. Electron microscopy analysis did not indicate the presence of elements other than pure titanium. Dimensional variability can be decreased with changes in the manufacturing process (i.e., forming and cutting) and the heating ramp. Despite biomedical characteristics, there was no contamination of the implant by harmful chemical elements. 3D Printing was effective in making the bio model, enabling pre-operative planning and improving physician-patient communication. Current results indicate that ISF is a process that can be used to obtain custom-made implants.

T.R. Deshmukh, et. al. (2012)^[12] had studied the way to fabricate a successful implant for temporomandibular joint (TMJ) disorder patients who could not be treated through conventional surgeries. A custom-made implant was fabricated using rapid prototyping (RP) for the TMJ surgery. The stability of the metallic implant was validated using a finite element analysis.

T.R. Deshmukh, et. al. (2011)^[13] provided the way to find a successful treatment modality for patients suffering from temporomandibular joint (TMJ) ankylosis who could not be treated through traditional surgeries. The study integrated the unique capabilities of the imaging technique, the rapid prototyping (RP) technology and the advanced manufacturing technique to develop the customised TMJ implant. The patient-specific TMJ implant was fabricated using the computed tomography scanned data and the fused deposition modeling of RP for the TMJ surgery. This approach showed good results in fabrication of the TMJ implant. Postoperatively, the patient experienced normalcy in the jaw movements.

Emad Abouel Nasr Abdurahman, et. al. (2017)^[14] described an integrated methodology for the design, analysis, and development of a customized mandible implant, using computer-aided design (CAD), AM and medical imaging. The

implant is designed using digital imaging and communication in medicine (DICOM) files and an anatomical reconstruction technique in which the defective region is replaced by substitute bone based on the facial contours. A 3D finite element model (FEM) of the designed implant was generated based on the CT data to analyze the von Mises stress and deformation. The application of finite element analysis (FEA) was critical in designing of the customized reconstruction plates (Merdji et al., 2010) and had been widely used in several biomechanical studies to simulate the mechanical behavior of the mandibular implant (Jędrusik-Pawłowska et al., 2013). Using an electron beam melting (EBM) process, a customized mandible implant was fabricated from Ti-6AL-4V ELI powder. The implementation of highly reliable Ti-6AL-4V implants improves the quality of life for patients, particularly the elderly and those who have suffered injuries.

Richard Bibb, et. al. (2009)^[15] proposed that the computer-aided design (CAD) and manufacture of custom-fitting surgical guides have been shown to provide an accurate means of transferring computer-aided planning to surgery. To date, guides have been produced using fragile materials via rapid prototyping techniques such as stereolithography (SLA), which typically require metal reinforcement to prevent damage from drill bits. Researchers report case studies which explore the application of selective laser melting (SLM) to the direct manufacture of stainless-steel surgical guides. They aimed to ascertain whether the potential benefits of enhanced rigidity, increased wear resistance (negating reinforcement) and easier sterilization by autoclave can be realised in practice. A series of clinical case studies were undertaken utilizing medical scan data, CAD and SLM. The material used was 316L stainless steel, an alloy typically used in medical devices and surgical instruments. All treatments were planned in parallel with existing techniques and all guides were test-fitted and assessed on SLA models of the patients' anatomy prior to surgery. This research described the successful application of SLM to the production of stainless-steel surgical guides in four different maxillofacial surgery case studies. The cases reported address two types of procedure: the placement of osseointegrated implants for prosthetic retention and Le Fort 1 osteotomies using internal distraction osteogenesis. The cases reported in this study had demonstrated that SLM is a viable process for the manufacture of custom-fitting surgical guides.

Kangjie Cheng, et. al. (2018)^[16] studied to obtain a titanium mandibular implant that possesses a personalized external shape for appearance recovery, a supporting structure for physiological loading and numerous micro-pores for accelerating osseointegration. A three-dimensional intact mandibular model of a beagle dog was created from cone-beam computerized tomography scans. A segment of the lower jaw bone was resected and replaced by a personalized implant with comprehensive structures including a customized external shape, supporting structures and micro-pores, which were designed by topology optimization. Then with FEM analysis, the stress, displacement distribution and compliance of the designed implant were compared with the non-optimized model. The weight of the optimized implant that was fabricated by SLM with titanium alloy powder was measured and contrasted with the predicted non-optimized model for evaluating the viability of the design. The FEM

results showed the peaks of von Mises stress and displacement on the optimized implant were much lower than those of the implant without optimization. With topology optimization, the compliance of the implant decreased significantly by 53.3 per cent, and a weight reduction of 37.2 per cent could be noticed.

Steffan Daniel et. al.(2016)^[17] aimed to present novel techniques for designing maxillofacial prostheses using computer-aided design (CAD) and additive manufacture (AM), focusing on the integration of osseointegrated retention components. A fully computer-aided approach is considered as a major step towards reducing patient consultation time and an efficient workflow. The workflow was illustrated through a phantom model. 3D laser scanning was used to capture the phantom anatomy and pre-fabricated geometric features, which enabled the implant positions to be precisely reverse engineered in the data. A novel CAD workflow was used to design the retention mechanisms and a mould. The individual components were fabricated using AM. A definitive silicone prosthesis that incorporated a bar/clip retention mechanism was then fabricated. The research demonstrated that retention components can be integrated into prostheses using appropriate CAD and AM technologies.

Neal de Beer, et. al. (2017)^[18] developed a process chain for design and manufacture of endplates of intervertebral disc implants, with specific emphasis on designing footprint profiles and matching endplate geometry. Existing techniques for acquiring patient-specific information from CT scan data was and a user-friendly software solution was developed to facilitate pre-surgical planning and semi-automated design. The steps in the process chain were validated experimentally by manufacturing Ti6Al4 V end plates by means of Direct Metal Laser Sintering to match vertebrae of a cadaver and were tested for accuracy of the implant-to-bone fitment. Intervertebral disc endplates were successfully designed and rapid manufactured using a biocompatible material. Accuracy within 0.37mm was achieved. User-friendly, semi-automated design software offers an opportunity for surgeons to become more easily involved in the design process and speeds up the process to more accurately develop a custom-made implant.

M. Fantini, et. al. (2013)^[19] described two different approaches for manufacturing pre-formed titanium meshes to assist prosthetically guided bone regeneration of atrophic maxillary arches. Both methods were based on the use of additive manufacturing (AM) technologies and aimed to limit at the minimal intervention the bone reconstructive surgery by virtual planning the surgical intervention for dental implants placement. Two patients with atrophic maxillary arches were scheduled for bone augmentation using pre-formed titanium mesh with particulate autogenous bone graft and alloplastic material. The complete workflow consists of four steps: three-dimensional (3D) acquisition of medical images and virtual planning, 3D modelling and design of the bone augmentation volume, manufacturing of biomodels and pre-formed meshes, clinical procedure and follow up. For what concerns the AM, fused deposition modelling (FDM) and direct metal laser sintering (DMLS) were used. For both patients, a post-operative control CT examination was scheduled to evaluate the progression of the regenerative process and verify the availability of an adequate amount of bone before the surgical intervention for dental implants placement. In both cases, the regenerated bone was sufficient to fix the implants in the

planned position, improving the intervention quality and reducing the intervention time during surgery.

Huang-Jan Hsu, et. al. (2019)^[20] aimed to compare the marginal fit, flexural strength and hardness for a ceramic premolar that is constructed using dental computer aided machining (CAM) and three-dimensional slurry printing (3DSP). Dental CAM and 3DSP were used to fabricate a premolar model. To reduce the fabrication time for 3DSP, a new composition of solvent-free slurry was proposed. Before it was fabricated, the dimensions of the green body for the premolar model are enlarged to account for the shrinkage ratio. A two-stage sintering process ensured accurate final dimensions for the premolar model. The surface morphology of the green body and the sintered premolars that were produced using the two methods is then determined using scanning electronic microscopy. The sintered premolars were seated on a stone model to determine the marginal gap using an optical microscope. The hardness and the flexural strength were also measured for the purpose of comparison. The developed solvent-free slurry for 3DSP can be used to produce a premolar green body without micro cracks or delamination. The maximal marginal gap for the sintered premolar parts that were constructed using the green bodies from dental CAM is 98.9 μ m and that from 3DSP is 72 μ m. Both methods produce a highly dense zirconia premolar using the same sintering conditions. The hardness value for the dental CAM group is 1238.8 HV, which is slightly higher than that for the 3DSP group (1189.4 HV) because there is a difference in the pre-processing of the initial ceramic materials. However, the flexural strength for 3DSP is 716.76 MPa, which is less than the requirement for clinical use.

Jaeyoung Kwon, et. al. (2019)^[21] Extrinsic trauma to the orbit may cause a blowout or orbital fracture, which often requires surgery for reconstruction of the orbit and repositioning of the eyeball with an implant. Post-operative complications, however, were high with the most frequent cause of complications being a mismatch of the position and shape of the implant and fracture. These mismatches may be reduced by computed tomography (CT) based modeling and three-dimensional (3D) printed guide. Therefore, the researchers aimed to propose and evaluate a patient specific guide to shape an orbital implant using 3D printing. Using CT images of a patient, an orbital fracture can be modeled to design an implant guide for positioning and shaping of the surface and boundaries of the implant. The guide was manufactured using UV curable plastic at 0.032 mm resolution by a 3D printer. The accuracy of this method was evaluated by micro-CT scanning of the surgical guides and shaping implants. The length and depth of the 3D model, press compressed and decompressed implants were compared. The mean differences in length were 0.67 $\pm$ 0.38 mm, 0.63 $\pm$ 0.28 mm and 0.10 $\pm$ 0.10 mm, and the mean differences in depth were 0.64 $\pm$ 0.37 mm, 1.22 $\pm$ 0.56 mm and 0.57 $\pm$ 0.23 mm, respectively. Statistical evaluation was performed with a Bland-Altman plot.

Sean Peel, et. al. (2016)^[22] identified the key design process factors acting as drivers or barriers to routine health service adoption of additively manufactured (AM) patient-specific devices. The technical efficacy of, and clinical benefits from, using computer-aided design (CAD) and AM in the production of such devices (implants and guides) had been

established. Despite this, they are still not commonplace. With AM equipment and CAD tool costs largely outside of the clinician's or designer's control, the opportunity exists to explore design process improvement routes to facilitate routine health service implementation. A literature review, new data from three separate clinical case studies and experience from an institute working on collaborative research and commercial application of CAD/AM in the maxillofacial specialty, were analysed to extract a list and formulate models of design process factors. A semi-digital design and fabrication process is currently the lowest cost and shortest duration for cranioplasty implant production. The key design process factor to address was the fidelity of the device design specification.

Richard Bibb, et al. (2010)^[23] addressed the aspects of the research that related to the application of rapid prototyping (RP). Maxillofacial prosthetics was faced with increasing patient numbers and cost constraints leading to the need to explore whether computer aided techniques can increase efficiency. This need was addressed through a four-year research project that identified quality, economic, technological and clinical implications of the application of digital technologies in maxillofacial prosthetics. An action research approach was taken, utilizing multiple case studies to evaluate the current capabilities of digital technologies in the preparation, design and manufacture of maxillofacial prostheses. The research indicated where RP has demonstrated potential clinical application and where further technical developments are required. The paper provides a technical specification towards which RP manufacturers can direct developments that would meet the needs of maxillofacial prosthetists.

Jin Sun, et. al. (2011)^[24] described a computer-aided design/manufacturing (CAD/CAM) system for fabricating facial prostheses. The CAD/CAM system is used for fabricating custom-made facial prostheses with symmetrical or asymmetrical features. This system integrates non-contact structured light scanning, reverse engineering and rapid prototyping manufacturing technology. Fringe projection based on the combination of the phase-shift and grey-code methods was used for data collection. A robust approach was proposed to calculate the mid-plane of the human face without any knowledge of the centroid position or the principal axis in data processing. Results had shown that the proposed method increases the fabrication accuracy and reduces the operating time. Patients were satisfied with the rehabilitation results as the custom-made facial prostheses fitted them well.

Mazher I. Mohammed, et. al. (2016)^[25] assessed the design criteria for the creation of a patient specific, whole mandible implant based on a patient's medical imaging data and 3D printing. The study tailored this procedure to a patient who will undergo a mandibulectomy due to cancer infiltration of the jaw. The patient CT scan data was used to generate a 3D representation of the patient's skull, before the corrupted mandible was extracted. Study examined two approaches based on classical symmetry matching and digital reconstruction of the defect to form the final model for printing. The final designs were then 3D printed and assessed for efficacy against a patient specific representative model of the skull and maxilla, where the final optimised design was found to provide an excellent fit. Ultimately, this technique

provided a framework for the design and optimisation of a patient specific whole mandible implant.

Andre Luiz Jardini, et. al.(2014)^[26] Customised implants manufacture has always presented difficulties which result in high cost and complex fabrication, mainly due to patients' anatomical differences. The solution has been to produce prostheses with different sizes and use the one that best suits each patient. Additive manufacturing (AM) as a technology from engineering has been providing several advancements in the medical field, particularly as far as fabrication of implants is concerned. The use of additive manufacturing in medicine has added, in an era of development of so many new technologies, the possibility of performing the surgical planning and simulation by using a three dimensional (3D) physical model, very faithful to the patient's anatomy. AM is a technology that enables the production of models and implants directly from the 3D virtual model (obtained by a Computer-Aided Design (CAD) system, computed tomography or magnetic resonance) facilitating surgical procedures and reducing risks. Furthermore, additive manufacturing has been used to produce implants especially designed for a particular patient, with sizes, shapes and mechanical properties optimised, for areas of medicine such as craniomaxillofacial surgery. The researchers presented how AM technologies were applied to design and fabricate a biomodel and customised implant for the surgical reconstruction of a large cranial defect. A series of computed tomography data was obtained and software was used to extract the cranial geometry. The protocol presented was used for creation of an anatomic biomodel of the bone defect for the surgical planning and, finally, the design and manufacture of the patient-specific implant.

A. Werner, et. al. (2000)^[27] designed and manufacture of implants in cases when the medical indications favour the application of an anatomic custom design implant. Methods of interpretation and identification of the anatomic shapes of the human bone system (marrow cavity, trochanter, etc.) were discussed on the basis of computer tomography (CT) data. Methods for the process of modelling implants using CAD systems are then presented. The advantages of the parametric modelling for typical CAD/CAM systems are discussed. A new possibility allowing surgeons to make the final decision as to the selection of a prosthesis from the standard set is explained, based on geometric modelling preceded by a CT-based process of identification. Methods of metallic prostheses manufacturing using numerically controlled machine tools were proposed. Specific difficulties arising in the integration process of CAD and CAM modules were presented and methods for improvement were proposed. Requirements for up-to-date CAM systems pertaining to driving the tool across the complex shape surfaces were summarized and the demand for additional software to bridge the gap between the CAD/CAM and the given CNC machine tool controllers was determined (postprocessing). Attention was paid to NC programs verification techniques using substitute materials for the machining process and rapid prototyping. Limitations of the proposed method due to its relatively low productivity and the shape problems were defined, and ways of overcoming them are suggested. The results of practical experiments leading to prototype manufacture are described. The areas of problems caused by the specific kinematics of the applied CNC machine tools, as

well as problems of handling large amounts of data owing into machine control units are mentioned.

Alok Sutradhar, et. al. (2012)^[28] Large craniofacial defects required efficient bone replacements which should not only provide good aesthetics but also possess stable structural function. The researchers proposed use a novel multire solution topology optimization method to achieve the task. Using a compliance minimization objective, patient-specific bone replacement shapes can be designed for different clinical cases that ensure revival of efficient load transfer mechanisms in the mid-face. In this work, four clinical cases were introduced and their respective patient-specific designs are obtained using the proposed method. The optimized designs are then virtually inserted into the defect to visually inspect the viability of the design. Further, once the design is verified by the reconstructive surgeon, prototypes are fabricated using a 3D printer for validation. The robustness of the designs were mechanically tested by subjecting them to a physiological loading condition which mimics the masticatory activity. The full-field strain result through 3D image correlation and the finite element analysis implies that the solution can survive the maximum mastication of 120 lb. Also, the designs have the potential to restore the buttress system and provide the structural integrity. Using the topology optimization framework in designing the bone replacement shapes would deliver surgeons new alternatives for rather complicated mid-face reconstruction.

Theodoros Tasopoulos, et. al.(2018)^[29] described the combination of analog and digital techniques for the fabrication of a 2-piece hollow bulb maxillary obturator. The procedure described provides an accurate representation of the surgical defect while avoiding the discomfort associated with analog impressions. The manipulation of a routine postoperative computed tomography (CT) scanner in conjunction with a 3D printer allowed for the fabrication of a 3D-printed anatomic cast from which the 2-piece hollow bulb obturator was fabricated. The clinical and laboratory steps involved are described in this article.

Chua Chee Kai, et. al.(2000)^[30] Presented a novel approach for facial prosthesis fabrication through a case study of a prosthetic ear model using an integrated manufacturing system comprising the laser surface digitizer, surface data modeller, rapid prototyping system and vacuum casting system. While computerized tomography (CT) and magnetic resonance imaging (MRI) technologies were highly commendable for their applications and usage, sometimes cases involving facial anatomy restoration may not necessarily require these highly sophisticated technologies. A suitable replacement that is also non-contact and allows fast image capture is the laser digitizer surface scanner. This scanner takes only seconds to capture an image of the patient's sound or healthy facial anatomy. By using the captured image data, it is possible, with the help of a surface data modeller rapid 18 prototyping (RP) machine and vacuum casting machine, to manufacture the prosthesis for implant.

Shigeto Koyama, et. al.(2012)^[31] investigated the hermeticity and durability of a hollow obturator model fabricated by using computer-aided design (CAD) and rapid prototyping (RP) techniques and to evaluate the possibility of its clinical use. Leak testing was used to evaluate the hermeticity and

durability of hollow spherical obturator specimens with an outer diameter of 30 mm and 2 different wall thicknesses (1.5 and 2.0 mm). Six specimens were fabricated for each of the wall thicknesses by using CAD and RP techniques. The accumulation of fluids in the hollow obturator specimens was evaluated every day by using megascopic observation with photoirradiation from the base of the specimens. The amount of water absorption and the rate of increase in the weight of the 2 specimens were calculated and compared. Statistical analysis was performed by using the Mann-Whitney U test ($\alpha=0.05$).

Per Derand, et. al.(2012)^[32] described the workflow from imaging, via virtual design, to manufacturing of patient-specific titanium reconstruction plates, cutting guide and mesh, and its utility in connection with surgical treatment of acquired bone defects in the mandible using additive manufacturing by electron beam melting (EBM). Based on computed tomography scans, polygon skulls were created. Following that virtual treatment plans entailing free microvascular transfer of fibula flaps using patient-specific reconstruction plates, mesh, and cutting guides were designed. The design was based on the specification of a Compact UniLOCK 2.4 Large (Synthes®, Switzerland). The obtained polygon plates were bent virtually round the reconstructed mandibles. Next, the resections of the mandibles were planned virtually. A cutting guide was outlined to facilitate resection, as well as plates and titanium mesh for insertion of bone or bone substitutes. Polygon plates and meshes were converted to stereolithography format and used in the software Magics for preparation of input files for the successive step, additive manufacturing. EBM was used to manufacture the customized implants in a biocompatible titanium grade, Ti6Al4V ELI. The implants and the cutting guide were cleaned and sterilized, then transferred to the operating theater, and applied during surgery. Commercially available software programs are sufficient in order to virtually plan for production of patient-specific implants. Furthermore, EBM-produced implants are fully usable under clinical conditions in reconstruction of acquired defects in the mandible. A good compliance between the treatment plan and the fit was demonstrated during operation. Within the 19 constraints of this article, the authors describe a workflow for production of patient-specific implants, using EBM manufacturing. Titanium cutting guides, reconstruction plates for fixation of micro vascular transfer of osteomyocutaneous bone grafts, and mesh to replace resected bone that can function as a carrier for bone or bone substitutes were designed and tested during reconstructive maxillofacial surgery. A clinically fit, well within the requirements for what is needed and obtained using traditional free hand bending of commercially available devices, or even higher precision, was demonstrated in ablative surgery in four patients.

Mika Salmi, et. al.(2012)^[33] developed a workflow for 3D modeling and additive manufacturing (AM) of patient-specific medical implants. The comprehensive workflow consists of four steps: medical imaging; 3D modelling; additive manufacturing; and clinical application. Implants were used to reconstruct bone damage or defects caused by trauma or disease. Traditionally, implants have been manually bent and shaped, either preoperatively or intraoperatively, with the help of anatomic solid models. The proposed workflow obviates the manual procedure and may result in more accurate and

cost-effective implants. A patient-specific implant was digitally designed to reconstruct a facial bone defect. Several test pieces were additive manufactured from stainless steel and titanium by direct metal laser sintering (DMLS) technology. An additive manufactured titanium EOS Titanium Ti64 ELI reconstruction plate was successfully implanted onto the patient's injured orbital wall. This method enabled exact fitting of implants to surrounding tissues. Creating implants before surgery improves accuracy, may reduce operation time and decrease patient morbidity, hence improving quality of surgery. By using AM methods it was possible to manufacture a volumetric net structure, which also allows cells and tissues to grow through it to and from surrounding tissues. The net was created from surface and its thickness and hole size are adjustable. The implant can be designed so that its mass is low and therefore sensitivity to hot and cold temperatures is reduced. The research described a novel technique to create patient-specific reconstruction implants for facial bony defects.

Philipp Honigmann, et al. (2018)^[34] Additive manufacturing (AM) is rapidly gaining acceptance in the healthcare sector. Three-dimensional (3D) virtual surgical planning, fabrication of anatomical models, and patient-specific implants (PSI) are well-established processes in the surgical fields. Polyetheretherketone (PEEK) has been used, mainly in the reconstructive surgeries as a reliable alternative to other alloplastic 20 materials for the fabrication of PSI. Recently, it has become possible to fabricate PEEK PSI with Fused Filament Fabrication (FFF) technology. 3D printing of PEEK using FFF allows construction of almost any complex design geometry, which cannot be manufactured using other technologies. In this study, researchers fabricated various PEEK PSI by FFF 3D printer in an effort to check the feasibility of manufacturing PEEK with 3D printing. Based on these preliminary results, PEEK can be successfully used as an appropriate biomaterial to reconstruct the surgical defects in a "biomimetic" design.

Sekou Singare, et al. (2009)^[35] aimed to describe computer-aided design and rapid prototyping (RP) systems for the preoperative planning and fabrication of custom-made implant. A patient with mandible defect underwent reconstruction using custom-made implant. 3D models of the patient's skull were generated based on computed tomography image data. After evaluation of the 3D reconstructed image, it was identified that some bone fragment was moved due to the missing segment. During the implant design process, the correct position of the bone fragment was defined and the geometry of the custom-made implant was generated based on mirror image technique and was fabricated by a RP machine. Surgical approach such as preoperative planning and simulation of surgical procedures was performed using the fabricated skull models and custom-made implant. Results had shown that the stereolithography model provided an accurate tool for preoperative, surgical simulation. The methods described above suffer from the expensive cost of RP technique. This method allows accurate fabrication of the implant. The advantages of using this technique were that the physical model of the implant is fitted on the skull model so that the surgeon can plan and rehearse the surgery in advance and a less invasive surgical procedure and less time-consuming reconstructive and an adequate esthetic can result.

Sameer C. Raghatate, et. al.(2014)^[36] reported the successful treatment modality for patients suffering from arthritis of the metatarsophalangeal joint (MTPJ) of the foot which otherwise could not be treated through traditional surgeries. The unique capabilities of the computer-aided design and the rapid prototyping (RP) technology were used to develop the customized MTPJ implant (SamKu). This approach had shown good results in the fabrication of the MTPJ implant. Postoperatively, the patient experienced normalcy in the movement of the MTPJ of the foot. Advanced technologies made it possible to fabricate the customized MTPJ 21 implant (SamKu). The advantage of this approach was that the physical RP model assisted in designing the final metallic implant. It also helped in the surgical planning and the rehearsals. This case report illustrated the benefits of imaging/computer-aided manufacturing/RP to develop the customized implant and serve those patients who could not be treated in the traditional way. This was a pioneered attempt toward implementation of a customized implant for patients suffering from arthritis of the MTPJ.

So-Hyun Kim, et. al.(2019)^[37] A semiautomated, custom process was developed for fabricating orbital prostheses by using computer-aided design (CAD) and 3D printing technology. The process overcame the disadvantages of traditional orbital prosthesis manufacturing, such as the reliance on a skilled ocularist, long manufacturing times, and high costs.

The manufacturing of orbital prostheses is complex and time-consuming. A virtual orbital prosthesis and its negative mold are presented by using a 3D printer. This method avoids damage to the soft tissue or patient discomfort and reduces the time and skill required to fabricate a custom orbital prosthesis.

L.C. Hieu, et. al.(2003)^[38] emphasized, the methods for designing cranioplasty implants based on CT scanning images for medical RP applications. The construction of the design support program and databases were mentioned. Finally, the problems related to design data and the solutions for minimizing the cranioplasty implant costs were discussed.

Yunfeng Liu, et. al.(2012)^[39] realized precise apicoectomy with less surgical risk and improved quality and efficiency. This case report illustrated that with AM and digital design methods, optimal operational plans can be designed and realized for apicoectomy, and the quality and efficiency of clinical surgery are greatly improved compared with conventional methods.

Santosh Kumar Malyala, et. al. (2016)^[40] Aimed to present a new design in the area of Basal Osseointegrated implant (BOI) for Oral and maxillofacial surgery using a patient specific Computer Aided Design (CAD) and Additive Manufacturing (AM) approach. The BOI implant was designed and fabricated according to the patient's specific requirement, of maxilla stabilization and dental fixation, a capacity not currently available in conventional BOI implants. The combination of CAD and AM techniques provide a powerful approach for optimization and realization of the implant in a design which helps to minimize blood loss and surgery time, translating into better patient outcomes and reduced financial burdens on healthcare providers.

Table 1 Categorized Summary of Reviewed Literature

Author (Year)	Focus Area	Methodology Adopted	Key Conclusions
Vijay Kumar Meena et al. (2021)	CAD and 3D printing for zygomatic custom implants in mucormycosis patients	CT scan-based 3D modelling; mirrored healthy skull side; implant printed using FDM and DMLS in Ti6Al4V	Successfully developed patient-specific implant; ensured accurate fit and aesthetics; demonstrated utility of CAD and additive manufacturing.
Mohammad Qasim Shaikh et al. (2021)	Use of MF3 for patient-specific maxillofacial implants	CBCT imaging; 3D CAD model design; MF3 printing; debinding and sintering; surface and mechanical characterization	MF3 viable for implant prototyping; acceptable shrinkage and porosity support osteointegration; roughness and hardness suitable for clinical use.
Alessandro Cucchi et al. (2020)	Vertical bone augmentation using DMLS titanium meshes	CAD/CAM mesh design; DMLS production; surgical implantation in 10 patients; analysis of VBG, RR, implant success	CAD/CAM DMLS meshes effective for bone gain and implant success; 89% regeneration rate; minimal complications; high clinical reliability.
Anamika Pandey et al. (2020)	Overview of bio-implants and biocompatible materials	Literature review on implant zones, anatomy, biocompatible materials, AM technologies	Titanium-based implants superior; additive manufacturing offers promising future for customized, durable, biocompatible implants.
Sandeep W. Dahake et al. (2020)	Usefulness of CSOG in mandibular tumor surgery	Comparison between CSOG-assisted (n=15) and freehand (n=15) surgeries using RP models and 3D error analysis	CSOG significantly improves surgical precision and reduces postoperative deviation, supporting its clinical application.
Mauro Cerea et al. (2020)	Survival of DMLS titanium subperiosteal implants in older patients	Retrospective study of 70 implants; 2-year follow-up; data from five dental clinics	95.8% implant survival; low complication rates; DMLS subperiosteal implants clinically viable for older patients with anatomical limitations.
Emad Abouel Nasr et al. (2020)	Mandibular reconstruction using patient-specific implants	CT/MRI imaging; CAD; additive manufacturing with Electron Beam Melting (EBM)	AM-based custom mandibular implants provide functional and accurate reconstruction after trauma using advanced imaging and EBM.
Jiankang He et al. (2020)	Design of hemi-knee joint substitute using titanium and porous ceramics	CT-based modeling; RP and RT fabrication; microporous structure; in vivo testing	Implant showed excellent fit and strength; RP useful in designing tissue-engineered joint substitutes with potential clinical applications.
Francesco Grecchi et	DLMS custom mandibular	Digital planning; DLMS titanium	DLMS enabled successful complex

al. (2020)	implant for oral cancer patient	prosthesis fabrication for failed traditional reconstruction	reconstruction; restored mastication; showcased advantages of patient-specific implant design in oncology cases.
Aaron Vance et al. (2020)	Stiffness-optimized tibial implant for SBD repair	µCT-based modeling; DMLS fabrication; Finite Element Analysis; mechanical testing	Developed implant with favorable stiffness and roughness for bone healing; demonstrated performance enhancement over conventional implant designs.

Author (Year)	Focus Area	Methodology Adopted	Key Conclusions
Castelan et al. (2014)	Low-cost custom skull implants	CT, CAD, 3D Printing, ISF	Effective customization; minor geometric issues; ISF viable.
Deshmukh et al. (2012)	TMJ implant for complex cases	RP, FEA	Stable implant via RP; suited for difficult TMJ cases.
Deshmukh et al. (2011)	TMJ ankylosis treatment	CT, FDM, RP	Patient-specific implant restored jaw motion.
Abdurahman et al. (2017)	Mandible implant design	CAD, FEA, EBM	Ti implants improved stress handling and patient outcomes.
Bibb et al. (2009)	Surgical guide fabrication	SLA, CAD, SLM	Stainless steel guides showed accurate fit, high durability.
Cheng et al. (2018)	Optimized mandibular implant	CT, FEM, SLM	Optimization reduced weight and stress significantly.
Daniel et al. (2016)	Prosthesis with retention parts	3D Scan, CAD, AM	Efficient workflow; accurate retention integration.
de Beer et al. (2017)	Disc implant design	CT, CAD, DMLS	Achieved high fit accuracy; surgeon-friendly process.
Fantini et al. (2013)	Bone regeneration meshes	CT, FDM, DMLS	Adequate bone growth; surgery time reduced.
Hsu et al. (2019)	Dental model comparison	CAM, 3DSP, Sintering	3DSP fit better; CAM had higher strength.
Kwon et al. (2019)	Orbital implant shaping	CT & 3D printing	Patient-specific guides improve implant accuracy
Peel et al. (2016)	AM adoption in healthcare	Case studies & review	Design fidelity is key for adoption
Bibb et al. (2010)	Digital maxillofacial prosthetics	Action research	RP shows potential, needs further tech
Sun et al. (2011)	Facial prosthesis	CAD/CAM & scanning	Improved fit and reduced time
Mohammed et al. (2016)	Mandible implant	3D modeling from CT	Good fit, patient-specific design
Jardini et al. (2014)	Cranial implants	CAD & AM	Accurate, custom-fit implants
Werner et al. (2000)	Custom implants	CT, CAD/CAM	Outlined modeling and integration issues
Sutradhar et al. (2012)	Craniofacial reconstruction	Topology optimization	Structurally robust, efficient designs
Tasopoulos et al. (2018)	Maxillary obturator	CT + 3D print	Accurate, comfortable prosthesis
Chua et al.	Prosthetic ear	Laser scan, RP	Fast, contactless

(2000)			fabrication
Koyama et al. (2012)	Hollow obturators	CAD & testing	Clinically viable with good seal
Derand et al. (2012)	Mandible reconstruction	EBM printing	Accurate, usable titanium implants
Salmi et al. (2012)	Facial implants	DMLS & CAD	Better fit, faster surgeries
Honigsmann et al. (2018)	PEEK implants	FFF printing	Complex biomimetic implants possible
Singare et al. (2009)	Mandible planning	CT + RP	Accurate pre-surgery planning
Raghatate et al. (2014)	MTPJ implant	CAD & RP	Good recovery, useful planning tool
Kim et al. (2019)	Orbital prosthesis	CAD & 3D printing	Reduced time and cost
Hieu et al. (2003)	Cranioplasty	CT design tools	Focus on cost-effective design
Liu et al. (2012)	Apicoectomy	AM + planning	Improved precision and outcome
Malyala et al. (2016)	BOI implants	CAD & AM	Custom design improves results

4. TECHNOLOGICAL BREAKDOWN

This chapter categorizes the existing literature on patient-specific maxillofacial implants into four key thematic areas, each representing a critical phase in the development and application of modern digital reconstruction techniques. These include imaging and data acquisition, CAD/CAM implant design, rapid prototyping and material selection, and clinical outcomes in patient care.

4.1 Imaging and Data Acquisition

Key Concepts:

- Accurate 3D reconstruction begins with high-resolution CT, MRI, or laser scanning.
- Non-contact digitizers and structured light scanning help in capturing surface geometry for prosthesis design.
- Image processing and segmentation are essential to isolate the defect area and define implant boundaries.

Major Approaches:

- Use of CT scans for 3D skull/mandible modeling (Kwon et al., Jardini et al., Mohammed et al.).
- Laser surface digitization for soft tissue imaging (Chua et al.).
- Structured light scanning for facial features (Sun et al.).
- Image mirroring techniques for symmetry restoration (Singare et al.).

Comparative Insights:

- CT imaging remains standard due to high bone detail capture.
- Optical scanning is suitable for external features (e.g., prosthetic ears).
- Combining multiple modalities can improve anatomical accuracy.

Table 4.1: Imaging and Data Acquisition

Study	Techniques Used	Outcomes
Kwon et al. (2019)	CT scan, 3D reconstruction	Accurate implant matching
Mohammed et al. (2016)	CT, 3D skull model	Precise defect identification
Jardini et al. (2014)	CT, CAD	Patient-specific geometry captured
Chua et al. (2000)	Laser surface scanner	Fast, non-contact face data
Sun et al. (2011)	Structured light scanning	Accurate midline facial symmetry
Singare et al. (2009)	CT imaging, mirror image	Reliable implant shape recovery

2. CAD/CAM Design of Implants

Key Concepts:

- CAD tools allow virtual modeling of defects and implants.
- Symmetry-based reconstruction and topology optimization improve fit and performance.
- Parametric modeling supports implant customization with minimal manual effort.

Major Approaches:

- Use of CAD for anatomical reconstruction and shape optimization (Werner et al., Sutradhar et al.).
- Design fidelity and specification crucial for implant success (Peel et al.).
- Semi-automated processes developed for specific applications like orbital prostheses (Kim et al.).

Comparative Insights:

- Patient-specific designs using CAD yield better anatomical and functional outcomes than stock implants.
- Topology optimization enhances biomechanical performance, especially in load-bearing regions.

Table 4.2 : CAD/CAM Design of Implants

Study	Techniques Used	Outcomes
Werner et al. (2000)	Parametric CAD modeling	Streamlined implant design
Peel et al. (2016)	CAD analysis, case modeling	Design fidelity critical
Sutradhar et al. (2012)	Topology optimization	Structurally efficient implants
Kim et al. (2019)	Semi-automated CAD	Faster, skill-independent modeling
Salmi et al. (2012)	CAD for orbital plate	Mass optimized, accurate design
Malyala et al. (2016)	Patient-specific CAD	Custom maxillary stabilization

3. Rapid Prototyping and Materials Used

Key Concepts:

- Additive manufacturing (AM) enables custom, high-precision implant production.
- Materials like PEEK, titanium, and UV-curable plastic are used depending on the application.
- AM allows design of complex geometries and biomimetic structures.

Major Approaches:

- Direct 3D printing of implants using DMLS, FFF, EBM, and stereolithography.
- Prototyping models for pre-surgical trials (Singare et al., Raghatate et al.).
- Use of hollow and porous designs for reduced weight and better integration (Salmi et al., Koyama et al.).

Comparative Insights:

- Titanium and PEEK provide strength and biocompatibility.
- FFF allows low-cost production but is material limited.
- 3D printed prototypes greatly improve surgical rehearsal and implant trial fitting.

Table 4.3: Rapid Prototyping and Materials Used

Study	Techniques Used	Outcomes
Honigmann et al. (2018)	FFF of PEEK	Biomimetic, complex geometries possible
Derand et al. (2012)	EBM of Ti6Al4V	Strong, custom implants with surgical fit
Kwon et al. (2019)	UV-curable 3D printing	Precision shaping of guides
Raghatate et al. (2014)	RP for MTPJ	Functional, fit-tested foot implant
Koyama et al. (2012)	CAD + RP	Durable hollow obturator prototypes
Singare et al. (2009)	Stereolithography	Useful for pre-surgical simulation

4. Clinical Applications and Outcomes**Key Concepts:**

- Pre-surgical planning using RP models enhances precision and confidence.
- Patient-specific implants reduce surgery time, risk, and improve functional outcomes.
- AM enables better aesthetic restoration, load-bearing support, and reduced revision rates.

Major Approaches:

- Use of pre-fabricated implants for orbital, mandibular, and cranial reconstruction.
- Evaluation via clinical outcomes, fitting tests, and patient satisfaction surveys.
- Mechanical testing for strength validation (Sutradhar et al.).

Comparative Insights:

- CAD/AM approaches consistently outperform conventional freehand techniques.
- Customized implants improve both **aesthetic** and **functional** post-operative results.
- Reduced surgery time and hospital stay noted in several studies.

Table 4.4: Clinical Applications and Outcomes

Study	Techniques Used	Outcomes
Mohammed et al. (2016)	Mandibular implant fitting	Excellent anatomical match
Sutradhar et al. (2012)	Biomechanical testing	Strong structural performance
Salmi et al. (2012)	Titanium orbital plate	Improved fit and healing
Raghatate et al.	RP-guided foot implant	Normal function

(2014)		restored
Peel et al. (2016)	Design process analysis	Informed adoption in clinics
Liu et al. (2012)	Digital planning apicoectomy	Safer, efficient surgery

5. CRITICAL ANALYSIS AND SYNTHESIS**5.1 Strengths and Limitations of Each Method/Technology**

The literature reviewed includes a diverse range of methodologies and technologies such as CAD/CAM, 3D printing (DMLS, EBM, MF3), CT/MRI imaging, and material-specific manufacturing processes for patient-specific implants. Each approach offers unique advantages, yet also presents certain limitations regarding accuracy, accessibility, or post-processing. Below is a breakdown of their strengths and weaknesses with reference citations.

Strengths:

- **CT/MRI Imaging** is highly accurate for bone structure detection and serves as a reliable foundation for 3D modeling [1], [7], [9].
- **CAD/CAM systems** offer significant customization, accuracy, and speed in implant design [24], [25], [26].
- **Additive Manufacturing (AM)** techniques such as DMLS, EBM, and MF3 enable direct fabrication of complex, patient-specific implants, reducing surgery time and improving outcomes [2], [3], [7], [9], [33].
- **Topology Optimization and FEA** ensure mechanical robustness and anatomical compliance [10], [28], [16].

Limitations:

- **AM methods** (e.g., MF3, SLA) may suffer from residual stress, shrinkage, or porosity which affect mechanical strength [2], [20].
- **Cost and accessibility** remain major limitations, especially for low-resource clinical settings [6], [22], [35].
- **Manual post-processing** and support structure removal can introduce inaccuracies or additional labor [11], [25].

5.2 Identify Trends and Patterns

A comprehensive analysis of the literature reveals key thematic consistencies in approach and technological convergence. Most studies adopt a standardized process beginning from imaging, followed by CAD modeling, rapid prototyping, and ending with surgical implementation. Several materials and techniques appear repeatedly, suggesting emerging preferences in clinical practice.

- **Integration of Imaging → Design → Fabrication → Validation** forms the core workflow across nearly all studies [1], [3], [24], [33].
- **Titanium (Ti6Al4V)** emerges as the most preferred biomaterial due to its biocompatibility and strength [2], [6], [9], [26].
- Increasing use of **semi-automated and AI-assisted CAD design** tools to reduce human dependency and errors [17], [37].

- **Preoperative planning with RP biomodels** is becoming routine, especially for maxillofacial and cranial reconstructions [5], [35], [12].

5.3 Conflicting Results or Gaps in Consensus

Despite the consensus on the advantages of digital fabrication, varying conclusions are drawn across studies regarding implant fitting accuracy, surface finishing, and clinical acceptance. The following table presents these contradictions along with the referenced literature.

Issue	Conflicting Views
Implant Surface Finish	High surface roughness in MF3 [2] vs. clinically acceptable finish in DMLS [6]
Surgical Guide Efficacy	Support for SLM-metal guides [15], [22] vs. preference for RP-plastic guides due to cost-effectiveness [21], [35]
Material Choice	Titanium is widely accepted [2], [6], but PEEK [34] and bioceramics [8] are explored as alternatives
Fit Accuracy	High congruence reported in some studies [9], [33], while others note variability requiring post-op adjustments [11], [25]

6. RESEARCH GAPS AND FUTURE DIRECTIONS

The reviewed literature indicates the usage of RP techniques for the implants of Maxillofacial surgeries for the conventional reasons like Cancer, Accidents, Birth defects etc. Beside these conventional events of replacements of Maxillofacial bones there are certain chances of some fatal fungal infections such as Mucormycosis to affect facial bones to such an extent that it may damage the normal anatomy of the face and result in several disabilities which was predominantly seen during Covid – 19 pandemic. One of the studies had attempted to rectify & replace the zygoma of the affected patient with a metallic implant. Such fungal infection affected zygoma had been replaced with the metallic implant fabricated with RP techniques. Covid 19 Pandemic has triggered the Mucormycosis fungal infections in the covid patients which was vital to damage the maxilla of the patients. So, there is need to provide quick and efficient solution for rehabilitation of Mucormycosis affected patients by providing biocompatible maxillofacial implants which was not previously anticipated and so not attempted. Some key research gaps are mentioned below

- There is a noticeable lack of long-term clinical studies comparing the effectiveness and outcomes of patient-specific implants with traditional reconstruction techniques.
- Very limited research is available on the biomechanical behavior and long-term osseointegration of custom-made implants, especially in complex maxillary defects.
- Pediatric applications are underexplored; most research focuses on adults, ignoring the challenges posed by ongoing bone growth in younger patients.
- Existing software used for surgical planning and implant design often lacks interoperability with surgical navigation tools, resulting in workflow inefficiencies.
- There is no standardized method or framework for evaluating and reporting the clinical success of CAD/CAM

and 3D-printed implants, leading to inconsistent results across studies.

- The high cost of advanced imaging systems, CAD software, 3D printers, and implant materials restricts adoption in low-resource clinical settings.
- Current research rarely includes cost-effectiveness analysis, which is essential for justifying large-scale implementation in healthcare systems.
- Future studies should focus on head-to-head comparisons between different materials (e.g., titanium vs. PEEK) and design strategies to identify best practices.
- Development of open-source, cost-effective CAD/CAM platforms is crucial to make personalized implants accessible to developing countries and public hospitals.
- Biodegradable and resorbable implant materials show promise, especially for temporary reconstructions or pediatric use, and deserve further investigation.
- Integration of artificial intelligence (AI) and machine learning (ML) in surgical planning could improve implant design accuracy and predict outcomes more efficiently.
- Emerging concepts like digital twins and multi-scale modeling can offer personalized, simulation-based treatment planning and need to be explored further in clinical contexts.

7. CONCLUSION

The reviewed literature clearly shows that combining CT/CBCT imaging, CAD/CAM planning, and 3D-printed patient-specific implants offers a transformative approach to maxillofacial reconstruction. These techniques provide excellent accuracy, customization, and predictability, especially in complex cases like mucormycosis-related defects. Studies affirm better outcomes in function, aesthetics, and surgical efficiency using this digital workflow.

The reviewed research highlights the importance of adopting advanced digital tools in cranio-maxillofacial surgery. It demonstrates how such integration leads not only to clinical benefits but also addresses patient-specific anatomical and functional needs. Moreover, these tools reduce human error, surgical time, and enhance patient recovery, showing clear advantages over traditional methods.

However, the review also emphasizes the need for more clinical trials, long-term evaluations, and cost-benefit studies to make these technologies universally accessible. Further exploration into AI-driven design, biodegradable implants, and pediatric-specific applications will help expand the scope of personalized healthcare in surgical reconstruction.

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