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Review

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3D Printing in Craniofacial Surgery

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Abstract

In the last few decades, the utilization of 3D printing has transcended its niche status to become an indispensable tool in medicine, and its ability to swiftly produce intricate geometries, coupled with its cost-effectiveness, has propelled its adoption across multiple surgical specialties, including plastic, abdominal, and orthopedic surgery. Notably, in plastic surgery, 3D printing has revolutionized several facets of patient care, spanning from the creation of anatomical models for surgical planning and medical education to the fabrication of custom implants and molds and the creation of surgical guides. This review delves into the expansive landscape of 3D printing applications within plastic surgery, examining the diverse modalities and materials employed. By leveraging advancements in printing processes and materials, surgeons are empowered to refine established techniques and develop novel solutions tailored to individual patient needs. As the technology continues to mature, its impact on plastic surgery is poised to deepen, promising further enhancements in surgical precision, patient care, and functional and aesthetic outcomes. This review underscores the transformative potential of 3D printing in shaping the future landscape of plastic surgery, driving continuous improvement and innovation in the field.

Keywords: 3D Printing, Surgical guides, plastic surgery, anatomical models

INTRODUCTION

Over the last several decades, 3D printing has rapidly evolved from a slow, costly, niche technique with poor fidelity to a well-established and critically important manufacturing process that has found a key role in a wide variety of industries. Its strengths lie in the ability to rapidly iterate designs, produce prototypes cheaply and with minimal waste, and easily produce models with geometries that would be difficult or impossible to replicate with subtractive machining strategies. Continual improvement in manufacturing processes and exponential uptake of this technology have resulted in a drastic decrease in both hardware and software costs, and 3D printing is now commonplace both in the workplace and the home. Within the medical field, the applications of 3D printing are widespread and include everything from simple anatomical models and aids to visualization, to surgical guides, splints, and custom implants. These techniques encompass a range of techniques, materials, and processes under the umbrella term of "3D printing", and these will be discussed in more detail in this review. Lastly, we will discuss the developing trend of "point-of-care 3D printing" in hospitals, and the potential impact this could have on patient care.

3D printing has a wide array of uses in surgery and is currently heavily used in surgical planning. In their systematic review, Tack *et al*. conclude that more than 60% of described 3D printing use in surgery concerns surgical guides, while 38% of the literature describes the creation of 3D-printed anatomical models[1]. Other reports have also mentioned the creation of 3D custom implants, molds for prosthetics and ear reconstruction, implant shaping, and models for patient selection. The main application of 3D printing in medicine remains clinical: since the early 2000s[2], it has been used in multiple surgical specialties and for a wide array of procedures[3]. The analysis of articles describing 3D printing for surgical procedures spans across various surgical fields. By papers reported to have included additive manufacturing techniques, orthopedic surgery leads with 45.18%, with procedures such as knee surgery (30.70%), hip and shoulder replacement (8.33% and 2.19% respectively), and hand (1.75%) surgery described in the literature. Maxillofacial surgery holds a significant portion at 24.12%, while cranial surgery procedures present 12.72% of reported papers and spinal surgery procedures employing 3D printing are at 7.46%[1].

In Orthopedic surgery, the impact of 3D printing technology is especially notable in instances of trauma and complex cases, where the visualization of the injury is needed for planning the right surgery[4]. Surgeries involving regions of complex anatomy such as the pelvis, spine, shoulder, knee, and joints have demonstrated the greatest necessity for utilizing this technology. Subsequently, Orthopedic surgeons find themselves relying heavily on 3D-printed models, especially for knee and hip replacement.[3] In Abdominal and General surgery, Pietrabissa *et al*. described a similar use of additive manufacturing, where, in addition to the printing of kidney and liver models for surgical planning, 3D printing was also used for anatomical comprehension of other structures of interest (pancreas, vessels, GI tract), training and simulation, and patient counseling[5]. Beyond its use in orthopedic surgery and other types of surgery, 3D printing has been strongly associated with Plastic and reconstructive surgery, specifically in craniofacial and maxillofacial surgery.

MATERIALS AND TECHNIQUES FOR 3D PRINTING

3D printing in surgery encompasses a broad spectrum of materials, each with unique properties and applications. Among polymers, vinyl polymers stand out for their versatility and suitability for surgical and dental applications[6,7]. Poly-ether-ether-ketone (PEEK) and Poly-ether-ketone-ketone (PEKK) are commonly used for custom implants and have similar applications. They are both heavily used in cranioplasty[8]. PEEK is a dimensionally stable high-performance thermoplastic, and PEEK biomedical implants are generally produced by milling from solid material using a computer-controlled cutting device. PEKK is a closely related thermoplastic with similar properties; however, PEKK implants can also be 3D-printed and, as a result, may have a more porous structure [Figure 1].

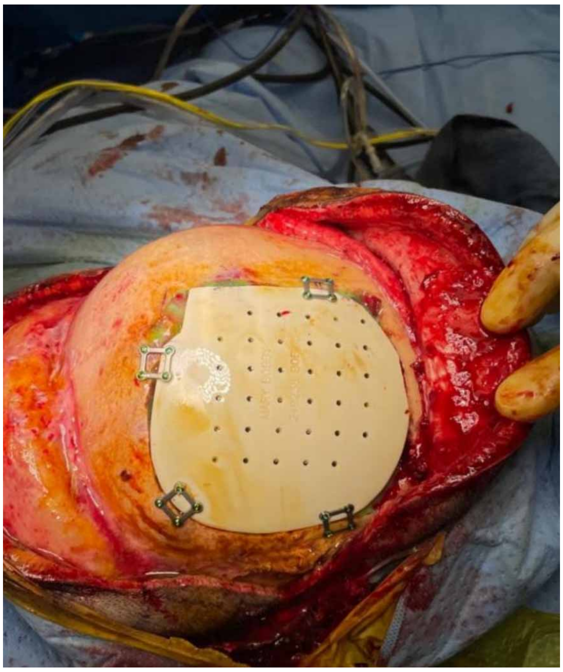

Figure 1. PEEK cranial implant used intraoperatively. PEEK implants are renowned for their dimensional stability and biocompatibility, making them ideal for covering large bony defects. PEEK: poly-ether-ether-ketone.

Porous polyethylene is another polymer that finds frequent application for cranioplasty, as well as elsewhere in facial skeletal surgery. While porous polyethylene is available in a wide variety of standard shapes that can be further modified, it may also be “printed” using a powder sintering technique in a pre-shaped mold cavity in order to create custom implants based on presurgical planning. Other types of polymers are also used in 3D printing, such as polystyrene (PS) and acrylonitrile-butadiene-styrene (ABS), which offer high transparency and mechanical strength, making them suitable for dental applications. Additionally, polyester polymers such as polycarbonate (PC), polycaprolactone (PCL), and polylactic acid (PLA) are also used and present biocompatibility and tunable properties, making them valuable in 3D printing for bone tissue regeneration and 3D-printed implants[9]. All materials used in 3D printing, as well as their advantages and disadvantages, are summarized in Table 1.

The cornerstone of medical 3D printing technology to date has been the resin 3D printer. These printers commonly use a technique known as stereolithography (SLA) printing. In this technique, prints are built up layer by layer using an ultraviolet light source to selectively cure a photosensitive resin. SLA resin printers can produce high-fidelity models with a resolution as high as 50 microns and with predictable material properties, and have found wide application within the medical field[10]. Stereolithography apparatus (SLA) printers operate by utilizing a laser to selectively solidify layers of liquid photopolymer resin. A laser beam is then directed onto the resin's surface, tracing the shape of each layer based on the sliced data, which constructs the 3D object. Another plastic 3D printing technology, Fused Deposition Modeling (FDM), uses a spool of thermoplastic filament which is melted and laid down layer by layer in the predetermined pattern to build the printed model. This technique, while widely utilized in rapid prototyping, manufacturing, and home user spaces, has not found the same application within the medical field, likely due to slower print times, lower fidelity models, and less predictable material properties[11].

Table 1. Overview of different materials for 3D printing and summary of their main advantages and disadvantages in plastic surgery applications

Material	Advantages	Disadvantages
Vinyl polymers	Versatile, suitable for surgical and dental applications	May not be suitable for high-stress applications
PEEK (poly-ether-ether-ketone)	High-performance thermoplastic, dimensionally stable, biocompatible, and strong	Expensive, limited to milling from solid material for implants
PEKK (poly-ether-ketone-ketone)	Similar to PEEK, can be 3D-printed for more porous structures, used in cranioplasty	Expensive, requires specialized 3D printing equipment.
Porous polyethylene	Suitable for cranioplasty and facial skeletal surgery, can be customized using powder sintering	Limited mechanical strength compared to metals, requires sintering equipment
Styrene polymers: polystyrene (PS), acrylonitrile butadiene styrene (ABS)	High transparency, good mechanical strength, suitable for dental applications	Lower biocompatibility, may not be suitable for long-term implants
Polyester polymers: poly(ε-caprolactone) (PCL), poly(lactic acid) (PLA)	Biocompatible, tunable properties, valuable for bone tissue regeneration and implants	May have lower mechanical strength, can degrade over time in the body

In addition to plastic 3D printing, the newer technologies of selective laser melting (SLM), selective laser sintering (SLS), and Electron Beam Melting (EBM) have opened the door to many new materials for custom guide or implant creation[12,13]. These techniques are used for ceramic and metallic implants creation, and are reported to enhance the rigidity of the implants. These techniques are closely related to SLA; however, the energy source utilizes a laser (SLS) or an electron beam (EBM) rather than a UV light (SLA). SLS is commonly used to build objects from plastic, glass, or ceramics, and as a result, has found application within the dental and prosthodontic fields[14], while SLM and EBM can be used to create custom geometric shapes from a *metal* substrate - commonly steel or titanium. The production of titanium guides and osteosynthesis plates with patient-specific geometries confers many potential benefits over more conventional methods, and these are becoming rapidly adopted as the gold standard for facial bony reconstruction cases[15]; an example of that application can be seen in Figure 2, which shows a patient-specific 3D-printed titanium plate.

COMPUTER-AIDED MANIPULATION TECHNIQUES FOR 3D MODELS

All 3D-printed constructs are created from a virtual three-dimensional (3D) model. Within the medical/surgical field, these 3D models are most often generated from the data output of imaging modalities such as computed tomography (CT) or magnetic resonance imaging (MRI) scans. In the case of anatomical reference models, it is relatively straightforward to generate 3D models using a variety of software. For more complex surgical planning, however, it is often necessary to manipulate the digital model in a variety of ways to generate a model with the desired geometry or anatomical features. In these cases, more complex and feature-rich software needs to be employed, such as Mimics (Materialize, Leuven) or Freeform (Geomagic/Artec 3D, Luxembourg). Using this type of software, a variety of manipulations are possible, and are described in the following Table 2.

Using a combination of these computer-assisted design (CAD) techniques, it is also possible to create new anatomy that can be used for more than simple anatomical reference in the operating room; the printed models can also be used as a structural scaffold upon which to build an intraoperative construct. For example, we have previously reported on the creation of a composite cranial vault model which combines the synostosis patient’s cranial base with the dural topology of a normative age-matched patient. This patient-specific composite model can then be used as a framework and scaffold, on which the calvarium can be rebuilt to the desired proportions on the back table[16]. This can be carried out while another team is obtaining hemostasis and barrel staving the cranial base, potentially shortening operative times [Figure 3].

Table 2. A list of digital manipulation techniques for three-dimensional models in preparation for 3D printing

Manipulation technique	Description
Mirroring of anatomy	Allows the unaffected or "normal" side to replace the affected side for unilateral conditions
Import of normative data	Enables importing 3D models from a library of normal anatomical features, scaled to fit the patient's anatomy for bilateral conditions or where no normal anatomy exists as a reference
Simulation of osteotomies	Digitally simulates bony osteotomy and differential movements within the 3D digital workspace, crucial for procedures like orthognathic surgery
Bony contouring	Digitally adds or subtracts from the bony skeleton using paintbrush or eraser-like tools to achieve desired shape or contour changes, applicable in surgeries like facial feminization

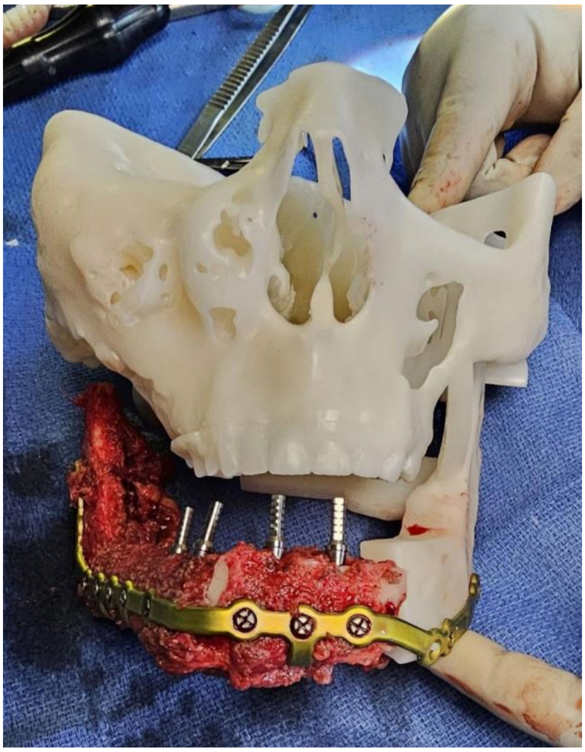

Figure 2. Patient-specific 3D-printed mandible reconstruction plate, serving as both an osteosynthesis plate and a positioning guide. The fibula neomandible is shown as plated in-situ in the leg, on a 3D-printed patient-specific skull model before rendering the flap ischemic and transferring to the face.

3D-PRINTED MODELS IN SURGICAL EDUCATION

Human Anatomy is a cornerstone of medical education, traditionally taught through hands-on approaches such as cadaver dissection. Not all medical schools have access to human cadavers for dissection due to financial and logistical reasons. Additionally, factors like increasing student numbers, reduced contact hours, and the time-consuming nature of dissection have further diminished its practice[17]. 3D printing has shown promise in various medical applications, including surgical planning and education[18]. Using medical imaging data, it is possible to create detailed models for teaching topographic and clinical anatomy. McMenamin *et al.*, in an early example of using 3D printing in medical education, describe their experience with printing and rescaling anatomical models of dissected limbs and hands, demonstrating the cost-effectiveness and speed of 3D printing[18] [Figure 4]. Subsequently, other teams successfully used 3D-printed models of the heart[19], brain, hand muscles, blood vessels and nerves of the hand[20], as well as the skull bones[17].

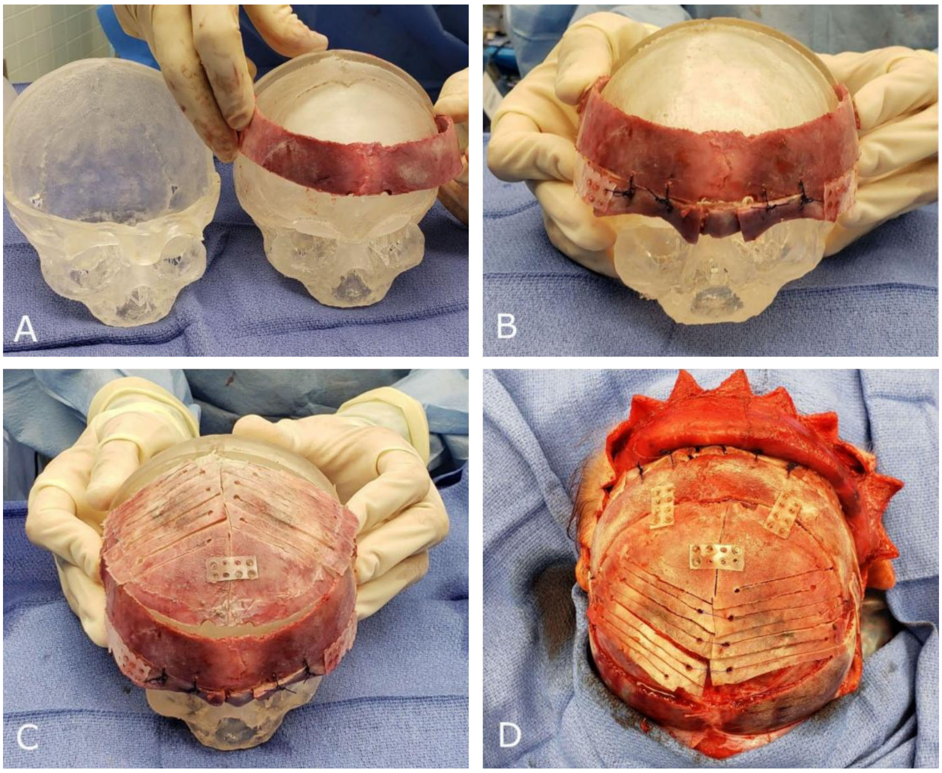

Figure 3. Patient-specific composite anatomy model that serves as a structural framework upon which the neocalvarium can be built. A-D: intraoperative sequence showing the framework being built, and then replaced on the patient.

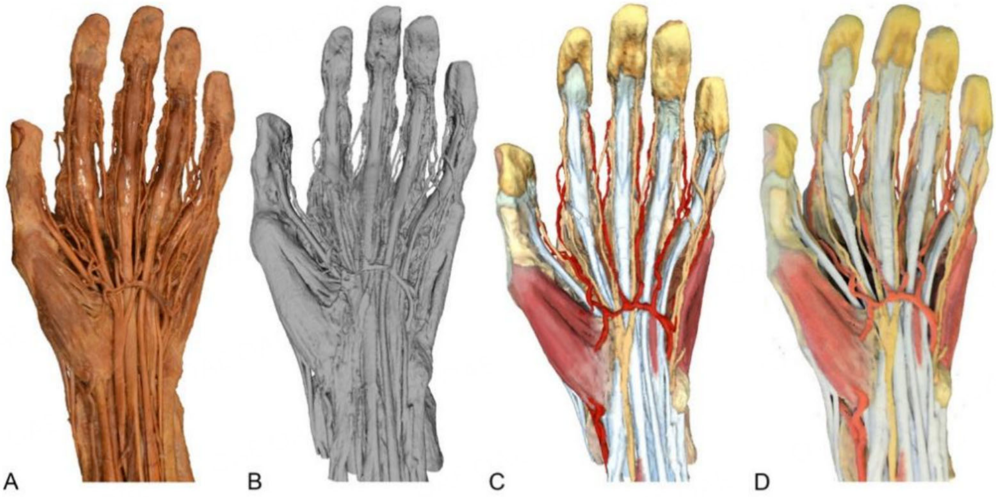

Figure 4. Prosection of the hand and wrist with 3D images and 3D-printed model (Used with permission from McMenamin *et al.*[18], © 2014 John Wiley and Sons. Licensed content number 5821111452734).

Within the field of plastic and reconstructive surgery, Yang *et al*. introduced 3D-printed skull bone models (3D-PSBs) using polylactic acid (PLA) to enhance medical education in skull anatomy. Students using 3D-PSBs showed significantly higher knowledge gains and increased clarity in visualizing skull structures[21]. In a similar way, Nicot *et al*. demonstrated that using 3D-printed models for craniofacial fractures improved medical students' understanding of the anatomy and helped contextualize haptic-visual data[22].

3D-PRINTED MODELS FOR PREOPERATIVE SURGICAL PLANNING

3D-printed models of both normal and pathologic anatomy can be used as surgical aids in the preoperative period. For the patient, these can serve as an important adjunct to the informed consent process, helping to demonstrate either the pathology or the proposed procedure[23]. For the surgeon, these aids can include anatomical reference models for visualization of complex anatomy or planning of osteotomies, as well as structural guides for the creation or modification of osteosynthesis plates, such as in craniomaxillofacial trauma. For example, Oliveira *et al*. demonstrated the application of 3D biomodelling technology and rapid prototyping for surgical simulation purposes. Clinical outcomes from 28 cases showed significant improvements in facial symmetry and functionality post-surgery, underscoring the substantial benefits of this innovative technique in enhancing patient outcomes[24]. Perioperative 3D models generally use a CT scan of the area of interest, which is exported into an .STL/.obj file representing a 3D model of the structure. This model is then 3D printed using biocompatible resins, and subsequently used for preoperative planning or intraoperative visualization[25]. This technique became a staple of surgical planning, where 3D-printed models serve as practical guides for surgeons. The use of such models has been linked to reduced costs[26], reduced operative times[27], improved surgical outcomes[28], and improved quality of life for patients[29,30].

A ubiquitous application of 3D printing in surgical planning resides in the pre-bending of reconstruction plates on 3D-printed mandibles. This was shown to improve mandibular contour compared to freehand plate bending in patients undergoing reconstruction after cancer ablation[31] [Figure 5]. Similarly, the use of 3D printed orbital models to pre-bend orbital implants has been shown to be a predictable method and provides excellent aesthetic and functional results[29].

In some cases where the loss of bone is extensive or the anatomy is otherwise distorted, a mirrored image of the contralateral anatomy can be used to provide a normalized 3D model that can then be printed. Park *et al*. (2015) used the normal uninjured side of the craniofacial skeleton, mirrored it, and created a rapid prototype skull model that resembled the individual skull model of the uninjured state; this model was subsequently sterilized for intraoperative use. The utilization of this 3D model resulted in esthetically satisfactory results and an improved contour[32].

3D-PRINTED MOLDS AND IMPLANTS

3D printing has also been described in the production of molds which can be used to make prosthetics and implants; in that case, the 3D-printed model serves as a base on which anaplastologists, technicians, or surgeons carve/mold the needed prosthesis out of material such as silicone. This method precedes other techniques and has been employed since the early 2000s. Müller *et al*. describe their successful experience using stereolithographic (3D-printed) skull models as the basis for sculpting suitable implants in clay; the master implant is then reconstructed on this model, using formable plastic material, thus achieving the outer contour[33].

Similarly, Yim *et al*. reported on the use of 3D anatomical models of the patient’s facial skeleton from the preoperative CT, upon which idealized implants were sculpted in modeling clay. Subsequently, silicone implants were fabricated using these molds, and implanted intraoperatively. The authors describe excellent outcomes, and report that their technique using molding and 3D printing was cost-effective, time-efficient, and accurate[34]. Li *et al*. reported a variation of this technique for chin augmentation, with the generation of 3D facial bone models, upon which an idealized virtual implant was created to create the desired volume and contour augmentation. Then, this virtual implant was 3D printed using a stereolithographic technique to create the prosthetic implant mold, which was subsequently used to make the individualized silicone implant[35].

Figure 5. Hand-bent plate on a 3D-printed model of a jaw. The jaw was printed using a preoperative CT scan, converted into a 3D model, and printed on an in-house 3D SLA printer.

Custom implants fabricated via additive manufacturing techniques have demonstrated promising potential in improving patient outcomes and reducing surgical complications[1,36,37]. Specifically, additive manufacturing techniques have emerged as effective modalities for accurately reconstructing the surgical anatomy of affected patients using patient-matched implants[37-39]. The use of custom- or patient-specific 3D-printed implants is primarily motivated by surgeons' necessity to address complex reconstructive scenarios requiring individualized interventions[40,41].

Custom 3D-printed implants are distinctively used in cranial surgery, dentistry, and maxillofacial surgery, with various benefits described in the literature[42]. Tack *et al.* report a decrease in operative times and treatment duration associated with the integration of custom implants, with multiple reports mentioning the commendable accuracy of tailored implants, and correlating their utilization with enhanced medical outcomes[43]. D'Urso *et al.* also suggest an increase in cost-effectiveness, warranting further investigation into the use of custom implants in craniofacial and plastic surgery[1]. There are numerous types and uses of 3D-printed implants: 3D-printed, patient-specific osteosynthesis plates are designed to stabilize fractures and facilitate bone healing, while ensuring optimal structural support[44].

3D-printed meshes are also used in orbital reconstruction and are designed to fit precisely in the patient's unique anatomy and have demonstrated excellent results restoring orbital or craniofacial integrity[37].3D printing can also be used to fabricate alloplastic augmentation implants, and have been described in nasal reconstruction[45], zygoma augmentation[46], and virtually all areas of the facial skeleton[47] [Figure 6]. With the versatility and accuracy afforded by 3D printing technology, these implants signify a paradigm shift in personalized plastic surgery interventions, promising improved outcomes and patient satisfaction.

In addition to their role in reconstructing shape defects, custom implants can also serve as positioning guides rather than solely as a fixation device[48]. This is only made possible by accurate registration of the custom implant to the patient's unique bony anatomy, which allows the implant to fit in only one possible position. In this way, 3D-printed implants can be relied upon to guide the reduction of facial fractures or to guide the positioning of an osteotomized jaw in 3D space, such as in orthognathic or jaw reconstruction surgery.

Figure 6. Planned reconstitution of facial defect using custom-made Medpor implant (Used with permission from Franco *et al.*[47], 2017. © 2017 Elsevier. Licensed content number 5754970485216).

The use of 3D-printed patient-specific implants encompasses all areas of bony reconstruction; if a need exists for a bone implant, whether for augmentation, contour, osteosynthesis or otherwise, the use of a pre-planned, patient-specific custom implant is likely to be more accurate, better adapted to the anatomy, and potentially lower profile compared with conventional alternatives. However, 3D-printed custom implants also have considerable disadvantages, namely lead time and cost. At the time of printing, the time required between the completion of surgical planning and the receipt of a patient-specific maxillary or mandibular fixation plate ranges between 7 and 11 business days. For many types of elective craniomaxillofacial surgery, this is acceptable and can be planned for without difficulty. However, this can severely limit the applicability of patient-specific implants, such as in the trauma setting when facial fracture repair may frequently be required within this timeframe. Further, the cost associated with custom implants currently far exceeds that of standard implants, often by a factor of 10x or more. This can also limit their applicability and may lead the surgeon to be more judicious in selecting patients most likely to benefit from this newer technology.

3D-PRINTED SURGICAL GUIDES: CUTTING, POSITIONING, AND DRILLING

Surgical guides represent the most prevalent surgical application of 3D printing technology, and are used widely, particularly for craniomaxillofacial surgery. A surgical guide serves as a crucial tool for enhancing surgical precision and accuracy during various procedures. These guides are typically designed based on detailed preoperative planning and imaging data, and subsequently 3D printed or created by subtractive manufacturing. The primary role of the surgical guide is to assist the surgeon in achieving optimal outcomes by providing guidance for incisions or osteotomies, bone or soft tissue repositioning, drilling, and implant or plate placement. By accurately delineating the desired surgical trajectory and landmarks, surgical guides help reduce intraoperative variability and facilitate more predictable results[49]. Additionally, they can contribute to shorter operation time[3], and improve overall patient safety and satisfaction.

The use of 3D-printed cutting guides is widespread in plastic surgery. The cutting guide is a 3D-printed construct with a narrow slot, designed to permit entry of the saw blade only in a specific vector and orientation and, therefore, permitting only the predetermined vector of cut. In orthognathic surgery, this has been described for a wide array of procedures. One of the earlier findings published about the successful use of 3D-printed guides was reported by Patel *et al*. in the 2000s [Figure 7]. They successfully implemented a workflow that integrates imaging with CAD/CAM to produce printed guides and models for surgery[15,50].

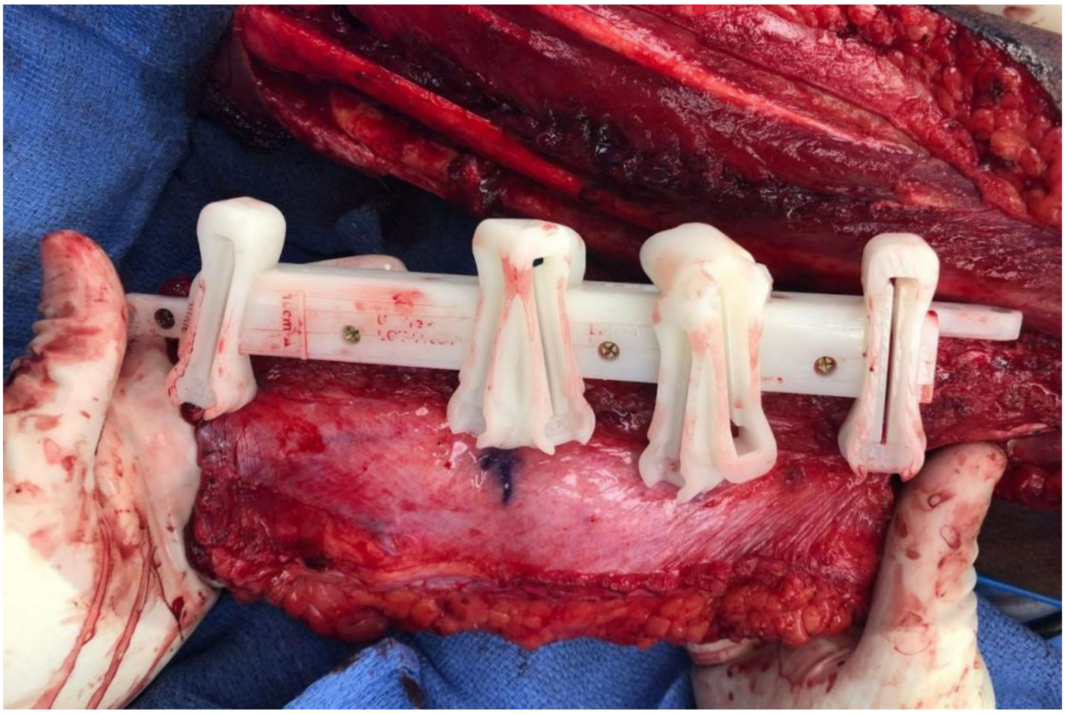

Figure 7. 3D-printed cutting guide for a fibula free flap. This cutting guide was produced using CAD techniques and designed under the supervision of the surgeon for the precise placement of osteotomies, aiming to achieve greater accuracy compared to the presurgical plan. CAD: computer-assisted design.

In the treatment of the ankylosis of the temporomandibular joint (TMJ), Haq *et al.* (2014) describe their experience with creating cutting guides in collaboration with an engineering team, and then using them for the total TMJ replacement procedures[51]. Ciocca *et al.* also describe a similar experience in complex mandibular reconstructions, where they successfully employed surgical planning, the CAD and manufacturing of 3D-printed mandibular cutting guides, fibular cutting guides (to ensure that the free flaps would fit accurately), and reconstructive plates[52]. In a similar context, Modabber *et al.* report their respective successful utilization of 3D-printed cutting guides for jaw reconstruction, with subsequent reduction in shaping time and ischemic time, and an improvement in flap survival[53]. Moreover, cutting guides are also used in other procedures, such as facial feminization, with reported safe and accurate use of such guides in surgical interventions done to the forehead, mandibular angles, and the chin[54].

Beyond cutting guides, additive manufacturing can also be used to create positioning guides. These can be used to accurately guide bone segments or implants into the correct position as determined by presurgical planning. Perhaps the most prevalent example of this is the use of 3D-printed occlusal splints to guide the position of the teeth, and therefore the jaws, during orthognathic surgery[55]. In other situations, a "bone-borne" positioning guide can be screwed to the bony anatomy, similar to a cutting guide. For example, Kozakiewicz *et al.* demonstrated the use of printed positioning constructs to help guide pre-bent orbital implants into the pre-planned position, with excellent results[56]. Similarly, Li *et al.* report their experience in using 3D-printed guides as a maxillary repositioning tool during Lefort I osteotomy, where the guides served a dual purpose for both cutting and repositioning of the maxillary segment[57]. Furthermore, 3D-printed guides can be used to direct drill hole placement, either for subsequent osteosynthesis plate placement (termed *predictive holes*)[58] or to set the vector for osseointegrated dental implant placement[59]. Abdel-Moniem Barakat *et al.* describe their use of drilling guides during bilateral split sagittal osteotomy

(BSSO) to maintain the virtually-planned condylar position and inferior alveolar nerve injury. Clinical evaluation showed good recovery of the maximal incisal opening and a reproducible occlusion in the patients, and the screws' position using the guides was deemed to be excellent[60].

With the more recent developments of metal 3D printing techniques and consequently the availability of true patient-specific osteosynthesis plates, the plate itself may, in fact, serve as a positioning device, helping to transfer the presurgical plan into the operative room through its semi-rigid nature, allowing the bone segments to fit in only the predetermined position[61]. This will be discussed in more detail later in this manuscript.

3D PRINTING IN EAR RECONSTRUCTION

Microtia is a congenital ear malformation that can affect the size, orientation, shape, and position of the external ear[62], and presents as a variable degree of absence of the ear auricle. Microtia, as well as other total (or partial) ear defects, can be treated through different clinical approaches involving reconstruction of the absent anatomy. Most of these approaches employ 3D printing in their workflow, such as auricular reconstruction with synthetic material implant, or auricular reconstruction with autologous tissue (costal cartilage harvested from the patient)[63,64].

The most frequently employed technique for microtia reconstruction is autologous ear reconstruction with a cartilage framework. The major difficulties of auricular reconstruction with autologous cartilage graft lie in the freehand carving and shaping of an auricular framework from the costal cartilage and in the definition of the minimum amount of cartilage required to obtain the reconstructed ear[65]. Currently, most surgeons approach autogenous microtia repair by creating a two-dimensional (2D) tracing of the unaffected ear. However, two-dimensional (2D) mirrored drawings lack the detail and 3D contours for proper reconstruction because they do not appropriately reproduce the complex features (i.e., height, depth, width, thickness, etc.) of the contralateral, unaffected ear[66,67].

Consequently, and as presurgical planning becomes a staple of modern surgery, a patient-specific and detailed 3D ear model is often used by surgeons intraoperatively to shape the ear, thus obtaining excellent esthetic and functional results[62]. Rodríguez-Arias *et al.* (2022) described their experience using a mesh processing software to segment and select specific components of the ear (helix, anti-helix -with both superior and inferior crura- and tragus) for 3D printing. These components would be printed and used intraoperatively [Figure 8] as guides for surgeons to carve the cartilaginous framework of the ear[68].

Another useful application of 3D printing technology can be found in a variation on the theme of positioning guides; in this case, it aids with determining the position of the new ear construct on the patient's head. In our practice, this determination is made jointly by the surgeon and anaplastologist through the review of the patient's preoperative photographs and videos, taking into consideration both the height of the contralateral ear, and the patient's resting head/neck posture. Once a decision has been reached, a partial face mask is designed, which registers on the patient's nose and malar prominence, and incorporates a marking guide to denote the pre-planned position of the ear. In this way, the exact positioning of the new ear construct can be accurately transferred from the digital plan to the patient in the operating room [Figure 9].

Auricular reconstruction can be done using synthetic 3D-printed scaffolds, imbedded with diced cartilage to promote regeneration: Jung *et al.* (2019) describe their use of a 3D-printed ear scaffold [Figure 10] using polycaprolactone (PCL)[45]. The 3D scaffold closely resembled the real cartilage framework used in current

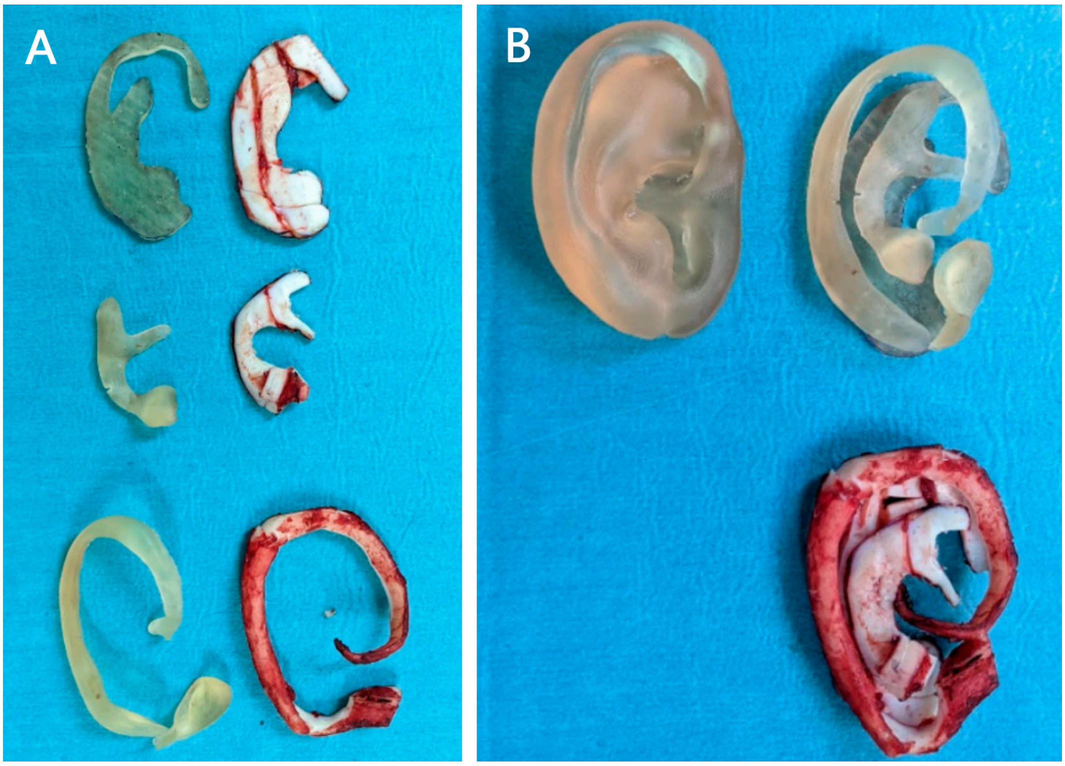

Figure 8. A: Each patient-specific 3D model together with its cartilaginous counterpart; B: final framework, with the two segmented and non-segmented models (Used with permission from Rodríguez-Arias *et al.*[68], 2022, an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license).


[redacted]

Figure 9. 3D-printed positioning guide for microtia reconstruction. The guide fits around the existing anatomy and allows the position of the ear construct to be clearly marked prior to incision.

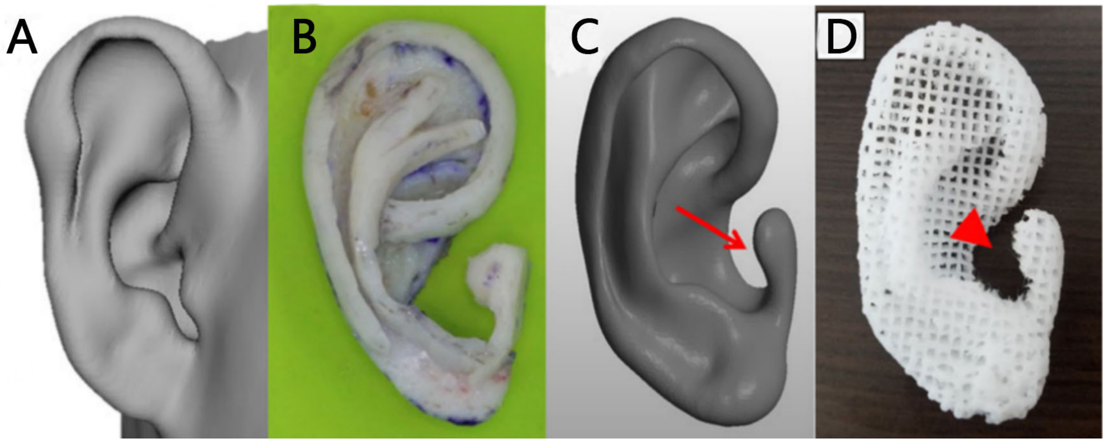

Figure 10. (A) Final result of the reconstructed 3D model (B) Real cartilage framework used in clinical ear reconstruction surgery (C) Modified design of the 3D scaffold to be suitable for Nagata's ear reconstruction surgery (D)3D-printed PCL structure. (Used with permission from Joo *et al.*[69], 2023, an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license).

operations in terms of ear anatomy. Joo *et al.* (2023) were able to design, fabricate, and apply patient-specific 3D-printed bio-scaffold ear implants [Figure 11] for 1st and 2nd stage ear reconstruction surgeries[69]. The early results of these reports show considerable promise, though long-term follow-up will be required before these novel techniques can be recommended to supplant more established cartilage-based reconstructions.

Porous Polyethylene auricular frameworks can also be used in lieu of a cartilage framework and present some unique advantages (and disadvantages) in comparison to cartilage. The primary advantage is the avoidance of donor site morbidity and the potential for improved detail in the reconstructed ear. The properties of porous polyethylene also allow for it to be "printed" or sintered into custom shapes, allowing a more exact match for the contralateral side if desired, while its porous structure allows for vascular ingrowth and its incorporation into the surrounding tissues. However, early experience with alloplastic ear frameworks revealed a high risk of framework extrusion when placed directly under the skin, necessitating the use of temporoparietal fascia flap coverage at the time of placement. This tempers the advantage of avoiding a donor site since a new donor site is added. However, despite this, the porous polyethylene framework remains an excellent option for many patients, and is capable of providing an aesthetically pleasing reconstruction with good outcomes[70].

LIMITATIONS OF 3D PRINTING

The adoption of computer-aided three-dimensional reconstruction in craniofacial surgery introduces substantial financial considerations. Costs vary based on institutional contracts with third-party providers for virtual surgical planning services and patient-specific custom implants. While our review notes significant surgical time reduction using presurgical planning and 3D Printing techniques, comprehensive cost-effectiveness comparisons across different procedures remain inconclusive. As the market for medical three-dimensional printing expands, further economic evaluations are essential[71].

Additionally, soft-tissue movement constitutes a contentious issue in 3D modeling and printing for craniofacial surgery. Unlike bone, soft-tissue response can be unpredictable due to varying impedance, potentially necessitating adjustments or abandonment of virtual surgical plans. This unpredictability is particularly critical in complex cases like cleft reconstruction and facial asymmetry, where precise soft-tissue

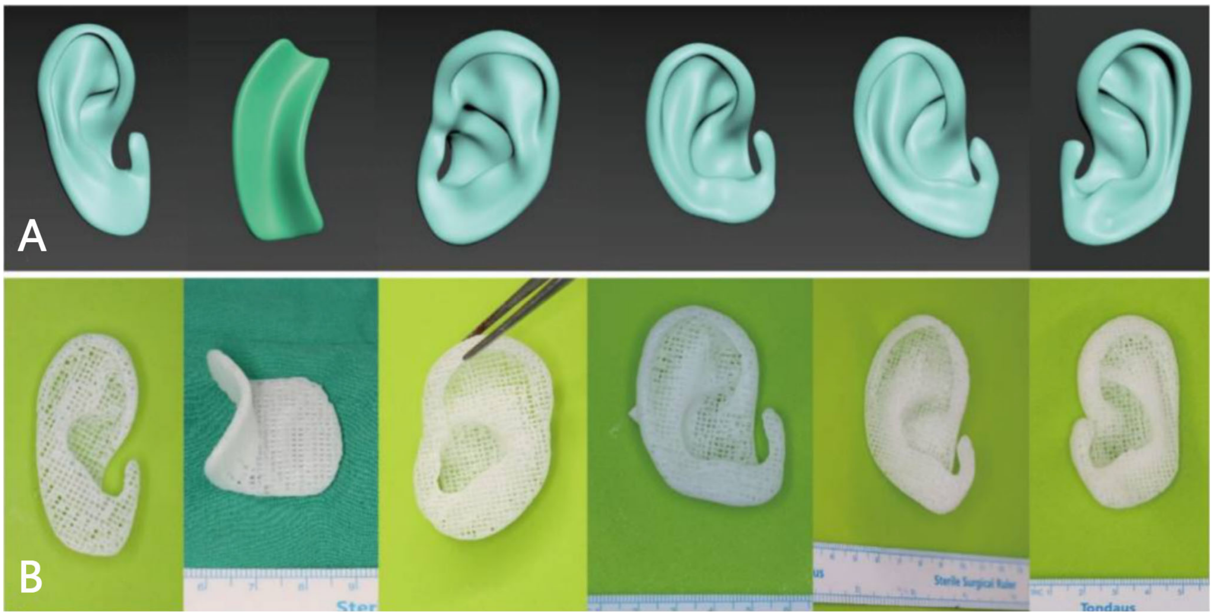

Figure 11. Design models (A) and the fabricated 3D-printed ear models (B) of the five patients who underwent ear reconstruction at our institute. 3D, three-dimensional (Used with permission from Joo *et al.*[69], 2023, an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license).

approximation significantly influences clinical outcomes.

Finally, despite the accuracy provided by 3D-printed molds, cutting guides and other intraoperative aids, situations arise where deviations from the virtual plan occur, thus compromising outcomes. Therefore, maintaining preoperative plans is crucial for achieving precise craniofacial reconstructions, especially in procedures requiring submillimeter accuracy, such as orbital wall reconstruction.

CONCLUSION

The evolution of 3D printing technologies has developed rapidly since its introduction, and it has been widely adopted within the medical and surgical fields. The wide variety of applications for this technology is a testament to its versatility, and it continues to present new opportunities through technological progress involving both processes and materials, allowing surgeons to continue innovating and improving upon established techniques. Today's anatomical reference models, cutting and drilling guides, and patient-specific implants are greatly improved from those available in previous decades, and will only continue to improve as the technology matures. The end result of this will undoubtedly be improved patient outcomes and satisfaction.

DECLARATIONS

Authors' contributions

Equally contributed to the literature review and manuscript preparation: Zeid NB, Arias E, Alkureishi LWT

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable. Figure was modified to hide any patient features, but additionally consent has already been taken from the patient at the time of surgery.

Consent for publication
Not applicable.

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