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SPECIAL TOPIC

Three-dimensional Printing in Plastic Surgery: Current Applications, Future Directions, and Ethical Implications

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Background: Three-dimensional printing (3DP) is a rapidly advancing tool that has revolutionized plastic surgery. With ongoing research and development of new technology, surgeons can use 3DP for surgical planning, medical education, biological implants, and more. This literature review aims to summarize the currently published literature on 3DP's impact on plastic surgery.

Methods: A literature review was performed using Pubmed and MEDLINE from 2016 to 2020 by 2 independent authors. Keywords used for literature search included 3-dimensional (3D), three-dimensional printing (3DP), printing, plastic, surgery, applications, prostheses, implants, medical education, bioprinting, and preoperative planning. All studies from the database queries were eligible for inclusion. Studies not in English, not pertaining to plastic surgery and 3DP, or focused on animal data were excluded.

Results: In total, 373 articles were identified. Sixteen articles satisfied all inclusion and exclusion criteria, and were further analyzed by the authors. Most studies were either retrospective cohort studies, case reports, or case series and with 1 study being prospective in design.

Conclusions: 3DP has consistently shown to be useful in the field of plastic surgery with improvements on multiple aspects, including the delivery of safe, effective methods of treating patients while improving patient satisfaction. Although the current technology may limit the ability of true bioprinting, research has shown safe and effective ways to incorporate biological material into the 3D printed scaffolds or implants. With an overwhelmingly positive outlook on 3DP and potential for more applications with updated technology, 3DP shall remain as an effective tool for the field of plastic surgery. *(Plast Reconstr Surg Glob Open 2021;9:e3465; doi: 10.1097/GOX.0000000000003465; Published online 22 March 2021.)*

INTRODUCTION

Three-dimensional printing (3DP) has revolutionized medicine and played a significant role in how physicians approach disease management. Although two-dimensional (2D) imaging [computed tomography (CT), magnetic resonance imaging (MRI), ultrasound (US), and x-ray (XR)] continue to be important in diagnosis and treatment, these modalities are largely unable to visualize images in three dimensions. Although 3D CT can effectively assess certain conditions (for instance, facial trauma), it lacks the critical components of 3DP such as tactile feedback and real-life spatial sizing. Broken down into 5 steps, 3DP allows for improved preoperative planning and has applications in creating custom surgical tools and prostheses, providing medical and patient education, and bioprinting (Fig. 1).[1]

3DP, otherwise known as additive manufacturing, was developed by Charles Hull in the 1980s and allowed for the production of physical objects from digital files.[2] Originally mainly focused on production of products for aerospace and automotive industries, the application of 3DP has expanded significantly. Similarly, use of 3DP technologies in medicine has been applied broadly over the last 2 decades. Within the field of plastic surgery, early applications of 3DP included presurgical planning (particularly in craniomaxillofacial surgery), fabrication of biocompatible

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Fig. 1. Five-step process of 3-dimensional printing.

prostheses, and educational tools for patients.[3] However, widespread implementation of 3DP has been limited by several factors, including high cost, inadequate accuracy, lack of readily available materials with appropriate properties for implantation, and minimal financial investment from the 3DP industry in medical applications.[2] As material costs decrease and precision increases, in conjunction with recent advances of 3DP technology, there is renewed scientific and clinical interest in 3DP applications in medicine, and in particular plastic surgery. Therefore, plastic surgeons, and consequently their patients, stand to significantly benefit from a working knowledge of 3DP and its potential role in plastic surgery.

As the utility and application of 3DP grows, physicians ought to understand its attendant capabilities, indications, and limitations. The aims of this article are 3-fold: the first aim includes performance of a literature review to summarize current evidence regarding 3DP technology in plastic surgery. Second, we discuss future directions of this technology within plastic surgery. Finally, we consider unique ethical issues that may arise when employing 3DP technology.

METHODS

A systematic review of electronically available publications available as of January 1, 2016 was performed. The focus was evaluation of recent advances of this technology as prior publications have highlighted earlier work.[2–7] The review was conducted in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Fig. 2).

Search Criteria

An all-language search in 2 databases (PubMed and MEDLINE) and manual inspection of citations in all articles identified from the online search were performed for publications between 2016 and 2020 by 2 independent authors (AQL and CMT). A third review served to adjudicate any disagreement. The following keywords were applied: three-dimensional (3D), three-dimensional printing (3DP), printing, plastic, surgery, applications, prostheses, implants, medical education, bioprinting, and preoperative planning. All returned studies from the database queries utilizing the aforementioned key words and search strategy were reviewed for applicability.

Exclusion Criteria

An initial title/abstract screen was performed to remove results not pertaining to 3DP and plastic surgery. Studies that failed to present novel data were excluded from the literature analysis. This included opinion papers, book chapters, and reviews. Additionally, studies without English or full text access were excluded. Animal studies were not considered.

RESULTS

The initial literature search identified 373 articles. Following initial review of titles and abstracts, 357 articles not addressing the application of 3DP in plastic surgery were excluded (Fig. 2). The remaining 16 articles satisfied criteria for inclusion.[8–19–23] Six articles were previous literature reviews.[2–7] Of the 16 articles, 1 article identified from this systematic review was prospective in design.[16] The remaining consisted of 10 retrospective cohort studies, 2 case series, and 3 case reports.

DISCUSSION

Surgical Planning

With regard to surgical planning, 3DP has assisted in numerous ways as detailed in a previous systematic review.[5] Plastic surgeons can utilize 3DP technology, allowing them to visualize defects and measure out the flap necessary to cover any defects or wounds in these reconstructive procedures.[5] More recently, 3DP has expanded to offer a way to precisely measure the amount of fat necessary for fat grafting when reconstructing facial defects. Arias et al report a case series of 6 patients with various hemifacial asymmetries who underwent imaging to create preoperative and postoperative masks.[8] The authors used the unaffected hemiface to measure the volume of fat needed to fill the defect of the affected side. Although facial fat grafting usually requires significant subjective decision-making by the surgeon, utilization of 3D printed masks to objectively measure volume achieved 80%–100% accuracy.[8]

3DP has been helpful in surgical planning in its ability to 3-dimensionally demonstrate the problem, the surgical plan, and proposed surgical outcome to not only the surgeon but also the patients. Several studies have assessed how surgeons and patients view the use of 3DP in surgery.[9,10] In a study of 25 patients undergoing facial feminization, La Padula et al found that 3DP was effective and also improved overall satisfaction and patient happiness using the Satisfaction With Life Scale and Subjective Happiness Scale.[9] Reported benefits of using a 3D printed model were the ability to plan surgery and to demonstrate to patients the expected postsurgical skeletal changes. Similarly, Guest et al reported that 3D printed models

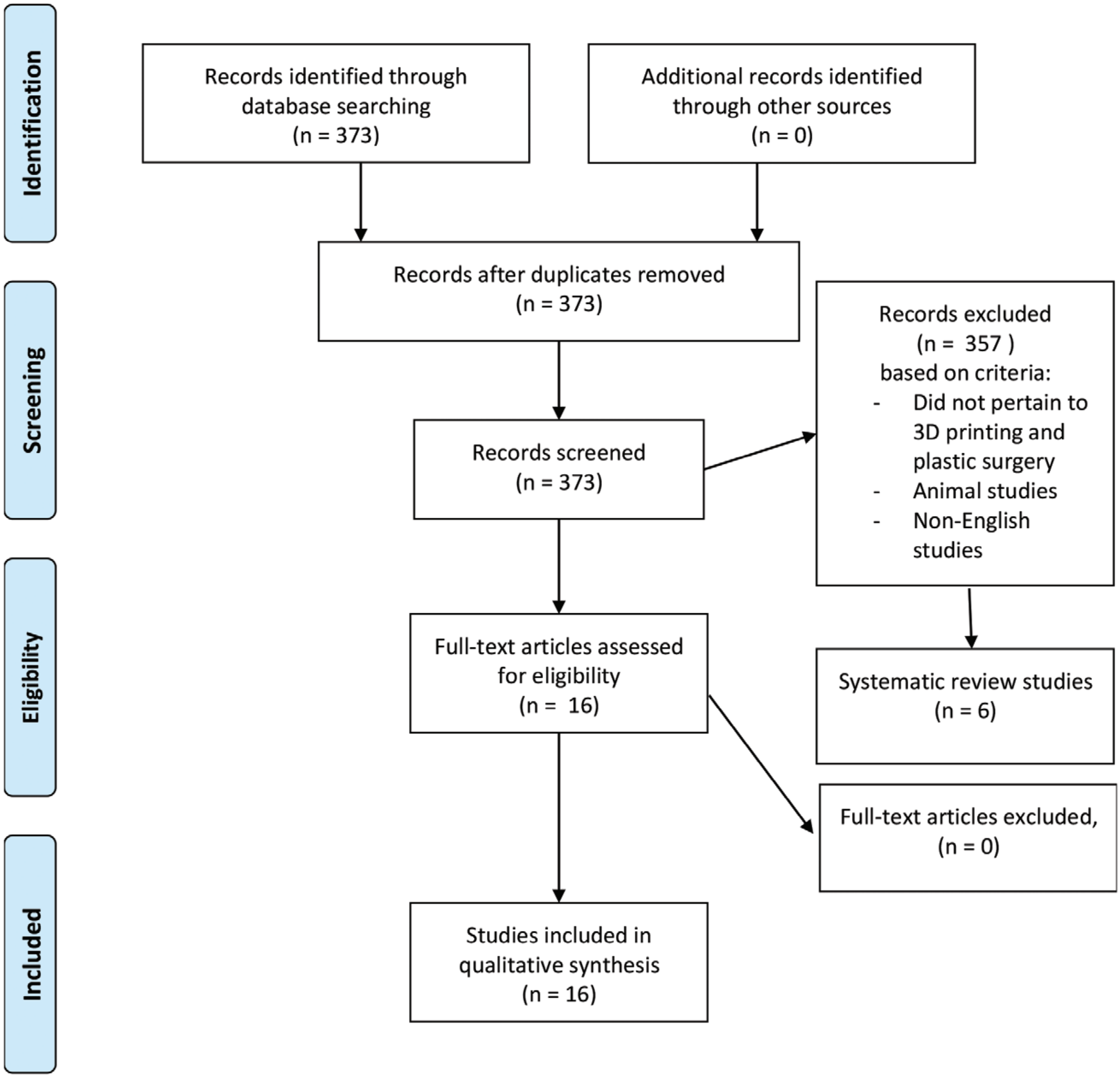

Fig. 2. Diagrammatic representation of the literature search schema.

increased confidence, and improved patient understanding and the informed consent process.[10] Although surgical planning centers on the surgeon's ability to achieve a successful outcome, it is also important to consider the patient's satisfaction and understanding of the procedures they are going through. All studies mentioned in this section are summarized in Table 1.

Intraoperative

3DP has also been used to assist surgeons intraoperatively. Chae et al employed 3D printed templates to visualize abdominal flap anatomy during breast reconstruction.[11] Citing a high rate of fat necrosis (8%–35%), 3DP was used to create a "perforasome template" to improve fat viability. The 3D template facilitated marking of the deep inferior epigastric artery and its perforators, and guided flap harvest.

In another study, authors used a 3D printed model to guide harvest of a chimeric iliac crest flap in a patient undergoing maxillectomy for maxillary osteomyelitis.[12] The guide optimized the surgical approach, resulting in smaller incisions, reduced bleeding, and improved cosmesis. The authors have also applied this successfully for mandible reconstruction. Additionally, Taylor et al successfully employed a home-based 3DP printer to facilitate upper extremity reconstruction with free tissue transfer, by creating a template of the flap, facilitating precise harvesting.[13]

3DP has also been used for nipple reconstruction and tattooing following mastectomy. Azouz et al created a 3D printed customizable nipple-areola stencil for office-based

Table 1. Surgical Planning

Year	Author	Summary
2019	Arias[8]	3D printed pre- and postoperative hemifacial masks of the unaffected side used to measure fill volume of fat to fill defect of the affected side.
2019	Guest[10]	3D printed models increase surgeon's confidence and improved patient understanding.
2019	La Padula[9]	3DP improves satisfaction and happiness of patients undergoing surgeries and can help explain surgical procedures to patients.

Table 2. Intraoperative

Year	Author	Summary
2020	Azouz[14]	Inexpensive and accurate 3D printed nipple-areola stencil used to simplify medical tattooing.
2018	Chae[11]	3D printed perforasome templates of DIEP to help guide flap harvesting to potentially reduce fat necrosis rates.
2019	Choi[15]	3D printed models of patient's cleft lip used both preoperatively and intraoperatively to improve visualization of relevant anatomy. The study also looked at enhancing resident education by utilizing 3D printed models as practice models for residents.
2017	Matias[12]	3D printed model chimeric iliac crest flap to improve outcomes for patients undergoing a maxilla or mandible reconstruction.
2017	Taylor[13]	3D printed model of free flap used to help upper extremity reconstruction to improve successful harvesting.

tattooing, which is both relatively inexpensive and accurate.[14] The device is a multi-layered stencil in which the operator can tattoo using a paint-by-numbers approach while implementing aesthetic principles of shading, coloring, and highlighting.

Lastly, Choi et al reported using 3DP in cleft palate repair.[15] Preoperatively, an intraoral scanner is used to produce 3D models that facilitate palate evaluation. The authors suggest that the model allows for improved visualization of palatal anatomy, surgical planning, and surgery. A further advantage was the enhanced resident education, as the models allowed residents to practice common procedures performed during cleft palate repair. All studies mentioned in this section are summarized in Table 2.

In the future, the concept of 4-dimensional (4D) modeling may become important. 4D is 3D printing with the factor of time added, allowing the surgeon to visualize how components interact with one another while in motion. Various models are printed out that depict motion of the organ, such as the hand. Although Chae et al has reviewed its use to visualize carpal bones in varying motions such as thumb adduction, no new studies have been found to further inquire its ability to enhance surgical planning.[5] Future ideas include determining adequate placement and stability of implants especially in areas with increased motion such as the joints of the hand, ankle, and feet as well as any craniofacial hinge structures. Other ideas include accurately identifying structures that may cause impingement, such as ulnar nerve entrapment or carpal tunnel syndrome, which may lead to novel treatment plans or avoid the possibility of unnecessary and outdated treatment strategies. To quantify and qualify this data, many studies must be conducted to look at clinical outcomes of 4D modeling to better understand its influence on surgeons and patients.

Medical Education

Many authors have reported on the effectiveness of 3DP in medical education.[16–18] A recent study employed 3D printed models in teaching medical students about cleft lip.[16] Compared with the control group (ie, no models), students who were given 3D printed models during instruction had an improved knowledge base of anatomy as well as satisfaction with the experience. Moving forward, studies comparing knowledge acquisition using 3D printed models and cadavers will be useful. Although there is no replacement for cadaveric dissection, 3DP adjuncts seem to be of significant value. To emphasize this point, 3DP has evolved to create more realistic training models. Podolsky et al have created a cleft lip surgery simulator that composes different material to represent the bone, muscle, cartilage, subcutaneous tissue, and skin.[17] Furthermore, dissection planes were thought out and incorporated into the model, giving a realistic surgical scenario where the Fischer anatomic subunit approximation technique could be used such as in the study. Although the study does not assess improved clinical outcomes or translation to real world scenarios, qualitative feedback by participants were positive and that the model will be a useful training tool.

In a study of surgical comprehension, Lobb et al found that 3D printed models improve understanding and reduce errors by residents when assisting in craniofacial procedures. Although limited by a small cohort, the article suggests that 3D models may improve understanding by effectively offering a preliminary experience of what to expect before the actual surgery.[18] All studies mentioned in this section are summarized in Table 3. Ongoing research will be useful in identifying how 3DP technology can be leveraged to improve medical education. Currently, there is evidence suggesting that 3DP can have a positive effect on medical education, as demonstrated by the aforementioned studies.[16–18] For an undergraduate level, more prospective studies will need to be conducted to determine whether 3DP assists in knowledge retention. These future studies can be done by comparing 3D printed models to traditional learning methods such as cadavers alone or as 3DP plus cadaveric instruction compared with cadavers. As for graduate level education, more translational studies need to be conducted to determine whether 3D printed models lead to improved patient outcomes. Some questions that arise are what outcomes are future studies assessing: aesthetic or decreased patient complications? Another challenge is controlling previous resident experience on certain surgeries that can influence outcomes. One possibility is to study plastic surgery interns who may

Table 3. Medical Education

Year	Author	Summary
2018	AlAli[16]	3D printed models of cleft lip demonstrated improved knowledge base of anatomy in medical students compared with using no 3D printed models.
2019	Lobb[18]	3D printed models may improve understanding of surgical procedure and reduce resident errors when performing craniofacial procedures.
2018	Podolsky[17]	3D printed high-fidelity models that accurately simulate cleft lip repair by utilizing different materials for various tissues and incorporating dissection planes.

Table 4. Prostheses/Implants

Year	Author	Summary
2018	Ahn[23]	3D printed mold injected with bone marrow stromal cells from the iliac crest to repair the patient's alveolar cleft. Six months later, the new bone had filled around 45% of the defect.
2017	Choi[19]	"3D Carving System" that allows for customizable, personal implants based off CT measurements for patients undergoing rhinoplasty.
2018	Han[22]	3D printed biodegradable implants used in maxillary reconstruction for complex defects with signs of tissue ingrowth and minimal bone formation over the implant degradation time of 3 years.
2018	Hirohi[21]	3D printed custom forehead implants to reduce appearance of temporal wasting.
2018	Khan[20]	Implementing the "3D Carving System" successfully in patients undergoing a secondary rhinoplasty following a prior nasal fracture.

start with a more equal knowledge base than senior residents due to varying experiences during residency.

Prostheses/Implants

The use of 3D modeling for custom implants is well established (Table 1).[5,24–26] Presently, 3DP has been employed to create custom molds in aesthetic surgery. Choi et al created custom negative molds with 3DP technology that has allowed for more personalized medicine.[19] The authors' "3D Carving System" consists of creating a patient-specific mold based off measurements obtained with preoperative CT. Once the mold is produced, curable silicone is injected, forming an implant to be used in rhinoplasty. Comparison of implant specifications to digital measurements demonstrated the accuracy and reproducibility of this method. No significant complications were reported. However, mild variation in the postoperative position of the implant when compared with the preoperative plan was observed, potentially due to inaccurate reflection of tissue elastic properties on CT. Given this, as well as the relatively small sample size, further study is important. A follow-up report by Khan et al demonstrated success with this technology in a patient with a history of prior nasal fracture undergoing secondary rhinoplasty.[20] This provided a proof-of-concept for 3DP to be applied in secondary rhinoplasty with a successful outcome.

In the case of forehead augmentation, Hirohi et al created a 3DP skull construct used to mold a custom forehead implant with temporal inserts to reduce the appearance of temporal wasting.[21] Methyl methacrylate was then shaped using the mold to fit the patient's forehead and was subsequently implanted successfully. Early results have been favorable, but further investigation is needed to assess long-term outcomes, patient satisfaction, and real-time aesthetic assessment.

Despite the advantages of custom-made implants, many of the materials are non-biodegradable. This theoretically increases the risk of inflammation, infection, and implant malposition.[22] To prevent these risks, Han et al used a 3D printed customized biodegradable scaffolding implant for stabilization and reconstruction of complex maxillary defects.[22] The scaffold degrades over a 3-year period. However, despite tissue ingrowth into the scaffold, minimal bone formation was noted. As such, further investigations will help elucidate 3DP biodegradable materials that promote bone regeneration.

3D printed implants have also been used in conjunction with stem cells. Cleft alveolus repair is traditionally performed with autologous bone grafting. Recently, Ahn et al created a 3D printed construct based off the alveolar cleft of a 10-year-old man undergoing alveolar bone grafting.[23] The mold was infused with bone marrow stromal cells extracted from the iliac crest before it was implanted and secured into the patient's alveolar cleft. At 6 months, new bone (bone mineral density between that of cancellous and cortical maxillary alveolar bone) had filled 45% of the defect. This technique aims to reduce complications associated with traditional autologous bone grafting, including donor site morbidity, prolonged operative time, risk of infection, and contour deformities.

Although 3DP has come a long way since it was first introduced, current technology is still limiting the potential of 3D bioprinting. Many of the materials used in 3DP begin to degrade in 3 weeks; however, when combined with bone marrow stem cells, the degradation process may extend to 6 weeks.[27] A future goal is to create a material that degrades just after bony healing has been sufficiently established.

Ethical Issues

Although innovation is critical to advance medicine, not all innovations are successful in improving patient care. This gives rise to the ethical dilemma of how to appropriately implement innovative strategies and how to monitor them. With respect to 3DP, there are many potential advantages to its use, including preoperative planning and individualized medicine, but this must be weighed against the ethical concerns regarding cost and availability (ie, justice).[28,29] Additionally, surgeons and institutions must be cognizant of conflicts of interest that can arise with development and implementation of novel technology. Indeed, there is significant potential for academic and financial gain.[30]

An additional important concern is ensuring appropriate informed consent by the patient. Patients must be advised of expected outcomes and risks but that they may not fully be understood or known when using new technology.[28–30] In particular to 3D printed devices made specifically for a patient, the attendant risks and benefits to the patient may be even more elusive.

Ethical recommendations with respect to 3DP include discussion with the patient regarding the newness of the devices, frequent outcome and safety review, and use of a national database for outcome reporting when feasible. Ongoing research is key to further understanding the benefits and potential pitfalls of this technology. Finally, surgeons must be aware of the potential for bias and conflicts of interest.[28–30] Innovation has revolutionized and improved patient care. It should be supported but frequently and critically appraised.

CONCLUSIONS

3DP has advanced the field of medicine significantly since its inception. In plastic surgery, it has proved to be a valuable tool preoperatively, intraoperatively, for medical education, and for improved patient satisfaction. Patient-specific constructs have facilitated delivery of safe and effective care, and have even allowed for increased happiness and understanding of surgery among patients. Although much work remains to better understand the indications, limitations, and outcomes associated with 3DP, early success in many areas within plastic surgery highlights its broad potential to improve patient care.

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