Customized "In-Office" Three-Dimensional Printing for Virtual Surgical Planning in Craniofacial Surgery

Bernardino M. Mendez, MD, Michael V. Chiodo, BS, and Parit A. Patel, MD

Background: Virtual surgical planning using three-dimensional (3D) printing technology has improved surgical efficiency and precision.[1–4] A limitation to this technology is that production of 3D surgical models requires a third-party source, leading to increased costs (up to $4000) and prolonged assembly times (averaging 2–3 weeks).[4,5] The purpose of this study is to evaluate the feasibility, cost, and production time of customized skull models created by an "in-office" 3D printer for craniofacial reconstruction.

Methods: Two patients underwent craniofacial reconstruction with the assistance of "in-office" 3D printing technology. Three-dimensional skull models were created from a bioplastic filament with a 3D printer using computed tomography (CT) image data. The cost and production time for each model were measured.

Results: For both patients, a customized 3D surgical model was used preoperatively to plan split calvarial bone grafting and intraoperatively to more efficiently and precisely perform the craniofacial reconstruction. The average cost for surgical model production with the "in-office" 3D printer was $25 (cost of bioplastic materials used to create surgical model) and the average production time was 14 hours.

Conclusions: Virtual surgical planning using "in office" 3D printing is feasible and allows for a more cost-effective and less time consuming method for creating surgical models and guides. By bringing 3D printing to the office setting, we hope to improve intraoperative efficiency, surgical precision, and overall cost for various types of craniofacial and reconstructive surgery.

Key Words: Three-dimensional (3D) printing, craniofacial reconstruction, surgical models, surgical guides

(*J Craniofac Surg* 2015;00: 00–00)

Reconstruction of complex craniofacial anomalies remains a challenging surgical endeavor. More recently, virtual surgical planning (VSP) using three-dimensional (3D) printing technology has improved surgical efficiency and precision through the production of 3D surgical models and guides.[1–4] Using computed tomography (CT) image data, 3D printers are able to create customized surgical models by producing successive layers of a bioplastic under computer control. These 3D surgical models and guides have been shown to be a valuable tool in preoperative planning and intraoperative decision making for bone and soft tissue reconstruction.[1,2,4–8] Preoperatively, these surgical models are used to more accurately estimate the amount and dimensions of autologous tissue or bioprosthetic material needed for reconstruction. In addition, they are used to plan and develop templates for cranioplasty and cranial vault remodeling procedures, splints for orthognathic procedures, and cutting guides for osteotomies.[1,2,5–7] Intraoperatively, the surgical models are used as templates for graft and implant fabrication to more efficiently and precisely reconstruct surgical defects. Using 3D models and guides has been shown to shorten operative time and potentially reduce the complications associated with prolonged operative times.[6–9] The main limitations to 3D printing are model assembly time and cost. Production of 3D surgical models requires outsourcing to third-party medical modeling manufacturers, which results in costs as high as $4000 and manufacturer-to-office assembly times ranging from 2 to 3 weeks.[4,5] The purpose of this study is to evaluate the feasibility, cost, and production time of customized skull models created by an "in-office" 3D printer for craniofacial reconstruction.

From the Department of Surgery, Division of Plastic and Reconstructive Surgery, Loyola University Chicago, Health Sciences Campus, Stritch School of Medicine, Maywood, IL.

Received October 28, 2014.
Accepted for publication February 1, 2015.

Address correspondence and reprint requests to Parit A. Patel, MD, Assistant Professor of Plastic and Reconstructive Surgery, Loyola University Medical Center, Stritch School of Medicine, Department of Surgery, 2160 South First Avenue, Maywood, IL 60153; E-mail: papatel27@hotmail.com

Supplemental digital contents are available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.jcraniofacialsurgery.com).
The authors report no conflicts of interest.

ISSN: 1049-2275
DOI: 10.1097/SCS.0000000000001768

MATERIALS AND METHODS

After obtaining approval from the Institutional Review Board at Loyola University Medical Center, a feasibility study was conducted where two patients with complex craniofacial defects underwent reconstructive surgery with the assistance of "in-office" 3D printing technology. Once informed consent was obtained, patient CT scan image data (1.25 mm slice cuts) was de-identified and burned onto a disc in a digital imaging and communications in medicine (DICOM) file format (Fig. 1). The DICOM file was then converted to a stereolithography (STL) file using an open-source program called Rapid3D (Rapid, Long Beach, CA). The STL file was next transformed into a 3D-model file using another open-source program called DeVide (Delft Visualization, GA Delft, the Netherlands) (Fig. 2). The 3D-model file was then sent to our "in-office" 3D printer, which created the surgical model/guide using a bioplastic filament composed of polylactic acid (Fig. 3; see Supplemental Digital Content, Video 1, *http://links.lww.com/SCS/A137*, which shows 3D-printing of skull model in action). The 3D printer used was a MakerBot Replicator (MakerBot Industries, Brooklyn, NY). Once the model production was complete, the cost and production time for each model was measured. The cost was based on the amount of bioplastic material used.

The 3D surgical models were then prepared for operative use with a low-temperature (18–35°C) sterilization technology called Sterrad (Advanced Sterilization Products, Irvine, CA), which uses hydrogen peroxide and gas plasma technology to sterilize surgical devices. Preoperatively, the surgical models were used to plan split calvarial bone grafting. Intraoperatively, the 3D surgical models

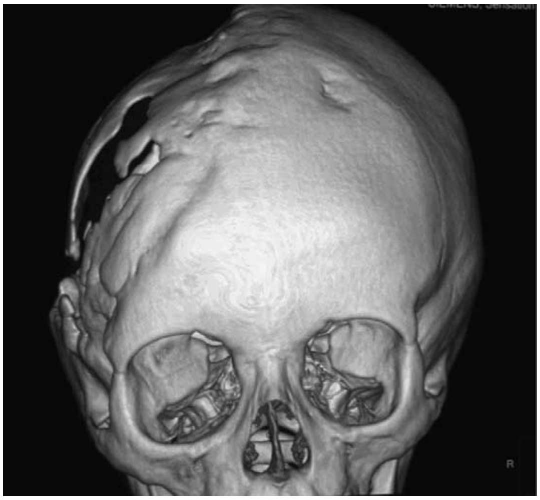

FIGURE 1. Three-dimensional CT image of 10-year old with a temporoparietal cranial defect.

were used as templates for bone graft fabrication and to more accurately perform the cranioplasty procedure (Fig. 4).

RESULTS

The first case involved a 10-year-old male with a temporoparietal cranial defect that occurred after resorption of a cranial bone flap following a craniotomy procedure for a subdural hematoma. The second case involved a 34-year-old male with comminuted, displaced frontal sinus, and orbital fractures because of trauma, who underwent a secondary craniofacial reconstruction. For each case, a customized 3D surgical model was created from CT image data and used preoperatively to plan split calvarial bone grafting, as well as intraoperatively to more accurately perform the craniofacial reconstruction. The cost for surgical model production using "in-office" 3D printing was $20 for the 10-year-old patient and $30 for the 34-year-old patient, with an average cost of $25. This accounted for the materials used to create the surgical models. Additionally, the surgical model assembly time was 12 hours for the 10-year-old patient and 16 hours for the 34-year-old patient, with an average

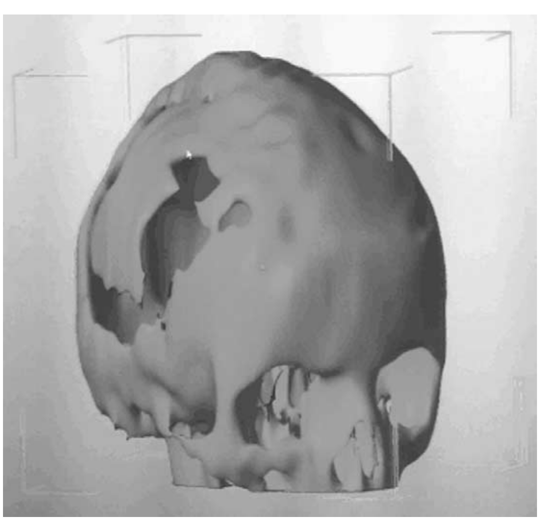

FIGURE 2. Three-dimensional model file, created from CT image data, ready to be sent to 3D printer.

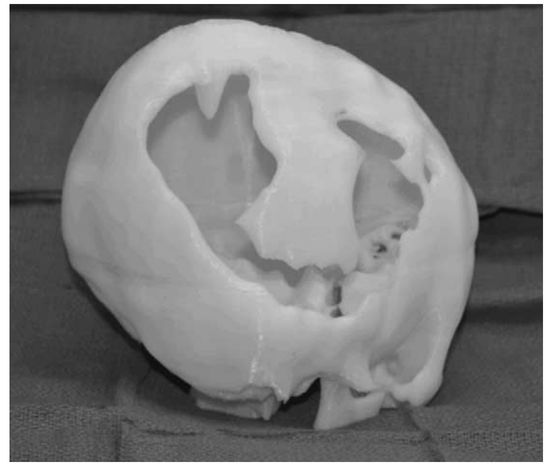

FIGURE 3. Three-dimensional skull model, created from bioplastic filament, of 10-year old with a temporoparietal cranial defect.

assembly time of 14 hours. The operative time for the cranioplasty of the 10-year-old patient was approximately 4.5 hours with an estimated blood loss of 250 cc. The patient's hospital stay was 4 days and he had no perioperative complications. The operative time for the frontal bone and orbital reconstruction procedure of the 34-year-old male was approximately 4 hours with an estimated blood loss of 25 cc. His length of stay was 2 days and he also had no perioperative complications.

DISCUSSION

Three-dimensional printing was developed over 30 years ago, however the technology has recently gained popularity in the medical field with applications in craniofacial reconstruction and vascular surgery.[4,6,7] Within the field of craniofacial surgery, 3D surgical models have been used as templates to create bone grafts, tailoring bioprosthetic implants, plate bending, cutting guides for osteotomies, and intraoperative oral splints.[1,2,5–7] By facilitating preoperative planning and intraoperative decision making, 3D surgical models have lead to improved surgical precision and efficiency along with reduced operative times. Mazzoni et al compared mandibular reconstruction using VSP with 3D printing

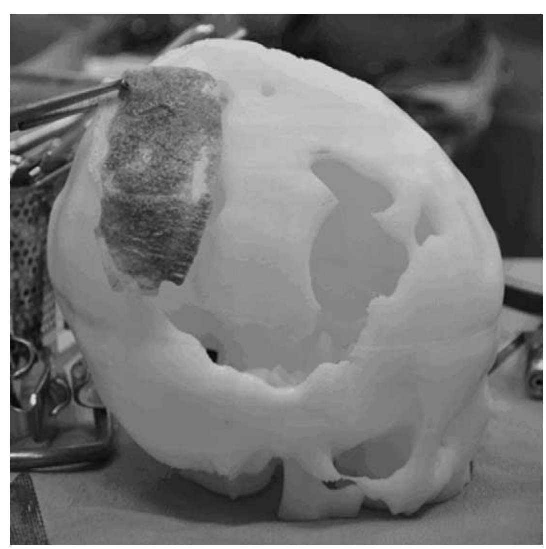

FIGURE 4. Using 3D surgical model as template for bone graft fabrication and to more efficiently and precisely perform the cranioplasty.

technology to reconstruction using traditional techniques (ie, computer designs of skulls created from CT image data). In their study, 3D surgical models were used as cutting guides for mandibular osteotomies and templates for fabricating fibular and iliac free flaps. The authors found VSP to be a safe method of mandibular reconstruction that allowed for accurate reconstruction of mandibular contour and reduced operative times.[6] Similarly, Cohen et al demonstrated reduced operative times when using VSP for plate bending and bone graft contouring in mandibular reconstruction.[7] In addition, they found VSP to improve surgical precision and reduce exposure to general anesthesia and blood losses. It is through applications such as these that VSP shows promise in playing an important role in the future of craniofacial and other types of reconstructive surgery. Using 3D surgical models has also been shown to be a valuable educational tool for patients and students/residents.[1,8] These surgical models and guides provide patients, family members, and trainees a unique hands-on 3D experience to better understand the defect and plan for reconstruction.

Despite the many benefits of VSP with surgical models and guides, current methods of 3D printing require outsourcing to medical model manufacturers, resulting in assembly times and costs that are considerably high. Expensive manufacturing fees and prolonged manufacturer-to-office turnaround times can be prohibitive in promoting the use and development of this technology. With an average cost and production time of $25 and 14 hours, respectively, our findings demonstrate that "in-office" 3D printing dramatically reduces cost and assembly time for surgical model production. Given the cost for a third-party source to manufacture one 3D skull model is on average $4000 and the cost to purchase a new 3D printer (with the size capacity to create a skull model) is approximately $2750, one would save a significant amount of resources and time by printing in the office setting. Once the cost of the "in-office" 3D printer is accounted for, the primary cost for surgical model production would be the bioplastic filament used to create each model. Given that a 2-pound spool of bioplastic filament costs on average $50 and approximately half of a spool is needed to create an adult skull model ($25), one could save approximately $3975 (depending on skull dimensions) by using "in-office" 3D printing as opposed to a medical model manufacturing company.

Despite the economic benefit of "in-office" 3D printing, some additional costs may result with this technology. One cost includes the maintenance and repair of the printer, which varies based on the 3D printer manufacturer. In regards to the MakerBot Replicator 3D printer, their company offers a service and protection plan for $350 per year which covers technical support via phone and email, as well as parts replacement. Another option is training the hospital's information technology (IT) staff to troubleshoot and repair technical issues. For example, a 3-hour training session by a MakerBot 3D printer specialist costs $225. An additional cost to consider is the physician's time and effort for the creation of the surgical guide, surgical splint, or skull model. At the time of study, when VSP involves a medical modeling company, reimbursement by insurance companies for 3D model creation is incorporated into the cost of the plating system and medical device cost. If "in-office" 3D printing were implemented, a current procedural terminology (CPT) code would have to be created, and the associated professional and facility fee assigned. The reimbursement for the physician and hospital services would have to be negotiated with third-party payers, medical insurance groups, and Centers for Medicare and Medicaid Services (CMS).

"In-office" 3D printing is a more cost-effective, less time consuming, and efficient method of creating 3D surgical models. With these findings, we hope to introduce "in-office" 3D printing as a more readily available, economical, and alternative to third-party surgical model production for various types of craniofacial and reconstructive surgery. In addition, 3D printing has many potential future applications besides VSP, including the creation of bioprosthetic implants and tissue engineering. Three-dimensional printing has recently been used to create customized printer-to-patient implants to directly reconstruct a craniofacial defect.[3] Other surgical subspecialties are researching the use of direct bioprosthetic implants for aortic valve leaflets, vascular bypass grafts, and tracheal stents.[11] Customized bioprinted implants would have great utility in reconstructive surgery, particularly with craniofacial reconstruction and maxillofacial surgery.

In addition to direct bioprosthetic implants, the future of 3D printing technology will be the ability to create biologic structures suitable for tissue transplantation or producing scaffolds for tissue engineering technology.[2] To engineer these biologic tissues, 3D bioprinters use natural polymers (eg, fibrin, collagen, hyaluronic acid) to create cells, which are then layered onto a scaffold and connected together by an extracellular matrix.[10] Bioprinters have been used to create a variety of tissues including multilayered skin, cartilage, bone, muscle, neurovascular structures, and kidney tissue.[11] Creation of these tissue types allows for boundless reconstructive options within the field of Plastic and Reconstructive Surgery. However, advancements in 3D printing may come with limitations including low cell viability and loss of cell function. In addition, strict regulation and testing would be required to ensure tissue compatibility with these engineered products. Nevertheless, by making 3D printing technology inexpensive and more readily available in the office setting, we hope to facilitate the advancement of 3D printing and evolution of reconstructive surgery.

ACKNOWLEDGMENT

The authors thank the staff at the Maker Lab in Harold Washington Chicago Public Library for their time and assistance in 3D printing of our surgical models.

REFERENCES

1. Chopra K, Manson PN, Gastman BR. Stereolithographic modeling in reconstructive surgery of the craniofacial skeleton after tumor resection. *Plast Reconstr Surg* 2012;129:743e–745e
2. Gerstle TL, Ibrahim AM, Kim PS, et al. A plastic surgery application in evolution: three-dimensional printing. *Plast Reconstr Surg* 2014;133:446–451
3. Chim H, Schantz JT. New frontiers in calvarial reconstruction: integrating computer-assisted design and tissue engineering in cranioplasty. *Plast Reconstr Surg* 2005;116:1726–1741
4. Gillis JA, Morris SF. Three-dimensional printing of perforator vascular anatomy. *Plast Reconstr Surg* 2014;133:80e–82e
5. Eppley BL, Sadove AM. Computer-generated patient models for reconstruction of cranial and facial deformities. *J Craniofac Surg* 1998;9:548–556
6. Mazzoni S, Marchetti C, Sgarzani R, et al. Prosthetically guided maxillofacial surgery: evaluation of the accuracy of a surgical guide and custom-made bone plate in oncology patients after mandibular reconstruction. *Plast Reconstr Surg* 2013;131:1376–1385
7. Cohen A, Laviv A, Berman P, et al. Mandibular reconstruction using stereolithographic 3-dimensional printing modeling technology. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2009;108:661–666
8. Emmez H, Küçüködük I, Börcek AO, et al. Effectiveness of skull models and surgical simulation: comparison of outcome between different surgical techniques in patients with isolated brachycephaly. *Childs Nerv Syst* 2009;25:1605–1612
9. Erickson DM, Chance D, Schmitt S, et al. An opinion survey of reported benefits from the use of stereolithographic models. *J Oral Maxillofac Surg* 1999;57:1040–1043
10. Moon S, Hasan SK, Song YS, et al. Layer by layer three-dimensional tissue epitaxy by cell-laden hydrogel droplets. *Tissue Eng Part C Methods* 2010;16:157–166
11. Murphy SV, Atala A. 3D bioprinting of tissues and organs. *Nat Biotechnol* 2014;32:773–785