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Real-time Reconstruction of Comminuted Mandibular Fractures Using 3D Printing

Dekel Shilo, DMD, PhD*†
Tal Capucha, DMD, PhD*
Andrei Krasovsky, DMD*
Ori Blanc, DMD*
Omri Emodi, DMD*†
Amir Haze, MD, PhD‡
Adi Rachmiel, DMD, PhD*†

Background: Comminuted fractures of the jaws are complex injuries requiring special attention. In the past, treatment included closed reduction using maxillomandibular fixation. With advancements in technology and fixation systems, open reduction became a prevalent option. These fractures are difficult to reconstruct during the primary treatment phase, thus resulting in higher complication rates. The introduction of three-dimensional (3D) planning and printing brought about superior outcomes, yet these focus on secondary reconstruction due to the need for outsourcing planning and titanium printing.

Methods: In this report, we describe real-time in-house 3D planning and printing using computer-assisted design software and a 3D-fused deposition printer for virtual reduction of the comminuted fractures and printing of the reconstructed mandible.

Results: Following virtual 3D reduction, the newly created mandibles were 3D printed. The model was then used to preband a reconstruction plate, which in turn was used as a template during surgery for reducing the segments. The process of virtual reduction and printing should take a couple of hours at most. The results of five cases showed good alignment and proper function.

Conclusion: Three-dimensional technology can be applied in the everyday primary care treatment protocol of comminuted fractures as an in-house tool which greatly improves both functional and aesthetic outcomes. *(Plast Reconstr Surg Glob Open 2024; 12:e5645; doi: 10.1097/GOX.0000000000005645; Published online 20 March 2024.)*

INTRODUCTION

Comminuted mandibular fractures usually result from a high-energy localized impact, most commonly secondary to high-velocity collisions or projectiles. Historically, these fractures were treated by closed reduction using maxillomandibular fixation (MMF) and external fixators.[1] These resulted at times in nonunion, malunion, or free bony segments undergoing infection and sloughing. With advancements in technology and fixation systems, open reduction became a predominant option.[2,3]

*From the *Department of Oral and Maxillofacial Surgery, Rambam Medical Care Center, Haifa, Israel; †Bruce Rappaport Faculty of Medicine, Technion-Israel Institute of Technology, Haifa, Israel; and ‡Department of Orthopedics, Hadassah-Hebrew University Medical Center, Jerusalem, Israel.*

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Drs. Shilo and Capucha contributed equally to this work.

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Comminuted mandibular fractures are difficult to reconstruct in the primary setup. Treatment begins with MMF, followed by rigid fixation. Many times, teeth are missing and/or basal fragments are not attached to their alveolar neighbors. These fractures require experienced surgeons familiar with what can be achieved in the primary treatment setup. Frequently, comminuted fractures require external incisions to allow for better control over the difficult reduction of the fragments. Complications following the treatment of these fractures are not uncommon. Most common are malocclusion, infection, and nonunion of the fracture.[4]

Personalized medicine is very trendy in most aspects of medicine and is greatly discussed both in the professional literature and in the news, mostly in the field of oncology.[5] When discussing personalized treatment in the surgical field, this usually means using the patient's imaging for personalizing their surgical plan. The introduction of three-dimensional (3D) planning and printing opened a

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whole new field for surgical expertise. Three-dimensional printing was first introduced and used for creating 3D models both for the civil and medical world.[6] Printing models allow for better preparation before surgery and preparing surgical aids and personalized fixation systems. For example, the use of 3D printing for presurgical adaptation of reconstruction plates in oncological resections.[7,8] Bergeron et al[9] showed the use of 3D printing for trauma patients. They describe the use of 3D reduction and printing in different facial fractures, yet in comminuted cases, they use a commercial provider, which results in a waiting period and in under preparation of the surgeon, as he did not restore the fractures himself.

With the development of both the virtual planning field and 3D printing technologies, the birth of patient-specific implants and surgical guides was another step forward. Since then, 3D planning and printing has become very abundant in several aspects of craniomaxillofacial surgery. Orthognathic surgery, for example, tended toward waferless surgery using surgical guides and patient-specific plates for highly accurate surgical movements of the jaws.[10] Secondary reconstruction is another field in which 3D planning gained popularity. For example, it has been used in mandibular secondary reconstruction using patient-specific implants following ablation surgery or major trauma.[11–14]

In contrast, using 3D planning and printing for primary care of trauma injuries is scarcely reported. Some surgical teams, having direct access to the manufacturing technology, show the use of patient-specific implants for primary treatment of orbital fractures.[15]

Here, we describe a method for immediate virtual reconstruction of mandibular comminuted fractures, followed by rapid printing of the reconstructed mandible for presurgical adjustment of the reconstruction plate, which in turn serves as a template for reduction of the displaced fragments, allowing for accurate reconstruction of the mandible.

Takeaways

Question: Comminuted fractures of the jaws are complex injuries difficult to reconstruct in the primary setup.

Findings: Simple in-house virtual three-dimensional (3D) reduction of comminuted fractures followed by 3D printing of the newly created bone. This was used as a template for adapting reconstruction plates, which resulted in superior outcomes.

Meaning: Three-dimensional technology can be applied in the everyday primary care treatment protocol of comminuted fractures as an in-house tool which greatly improves functional and aesthetic outcomes.

MATERIALS AND METHODS

Five patients with comminuted mandibular fractures were treated using this method. Two of the cases are presented here, one with severe comminution of the symphysis and body of the mandible due to a gunshot wound (GSW). The second had multiple fractures in the body of the mandible due to a collision with a multirotor drone. Both patients underwent CT upon arrival to the emergency room.

For the virtual planning, computer-assisted design software was used. The program used for the segmentation was D2P software (DICOM to Print, 3D systems, Ore.). The purpose of this software is to perform a segmentation of the desired bone intended for manipulation, in our case the mandible. This software receives the Digital Imaging and Communications in Medicine Format files from the CT, and following the separation of the desired bone, it creates a stereolithography (STL) file. D2P allows creation of different meshes for each fragment intended for manipulation and also for removing foreign bodies and artifacts. Using the "set threshold" function, we can separate foreign bodies and soft tissue as a first stage. Next, you can use the "automatic bone segmentation" for separating the large fragments and "manual segmentation" for the smaller fragments. Following the separation of the different fragments in D2P, the file is exported in STL format. The second program used was Geomagic Freeform (3D systems). This software allows for the manipulation of the bone and the creation of surgical guides and implants. The exported STL file from D2P is imported to the Freeform software. It maintains the current spatial relation of the fragments. At this point, each fragment can be repositioned to its anatomic position using the "reposition" function. Due to the minor voids created by the comminution the "add clay" function can be used for filling the small gaps in the bone. Next, the "smooth" function can be used to achieve a continues surface. Detailed protocols for using these software for reconstruction purposes, orthognathic purposes, and patient-specific implants can be found in our previous articles.[16,17]

The 3D printer used for printing the reconstructed mandible was a fused deposition modeling (FDM) printer Ultimaker 3 (Ultimaker B.V., Utrecht, the Netherlands).

Table 1. Patient Characteristics

Follow-up (Mouth Opening)	Operation Length, min	TMJ Affected (Yes/No)	Dentition Status	Injury Mechanism	Age, y	Sex (M/F)	Patient
ND	258	No	PD	MW	21	M	1
FMO	340	No	FD	GSW	24	M	2
FMO	250	No	PD	Drone accident	47	M	3
FMO	259	No	PD	GSW, SA	21	M	4
ND	367	No	PD	GSW	37	M	5

F, female; FD, full dentition; FMO, full mouth opening; M, male; MW, missile wound; ND, not detailed; PD, partial dentition; SA, suicide attempt.

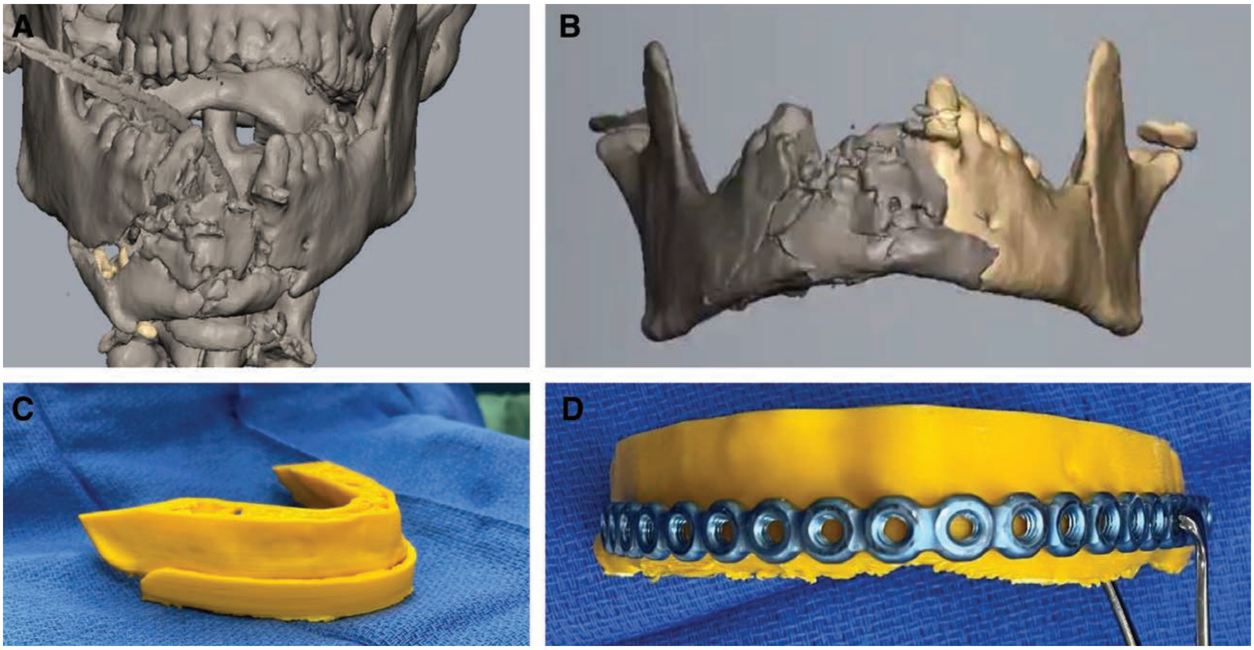

Fig. 1. Three-dimensional planning and printing. A, The comminuted mandible in Freeform software following segmentation and before reduction. B, Following reduction of the fragments. C, The 3D-printed recreated mandible and a template of the lower border for easy reduction of the fragments. D, Plate adaptation before surgery.

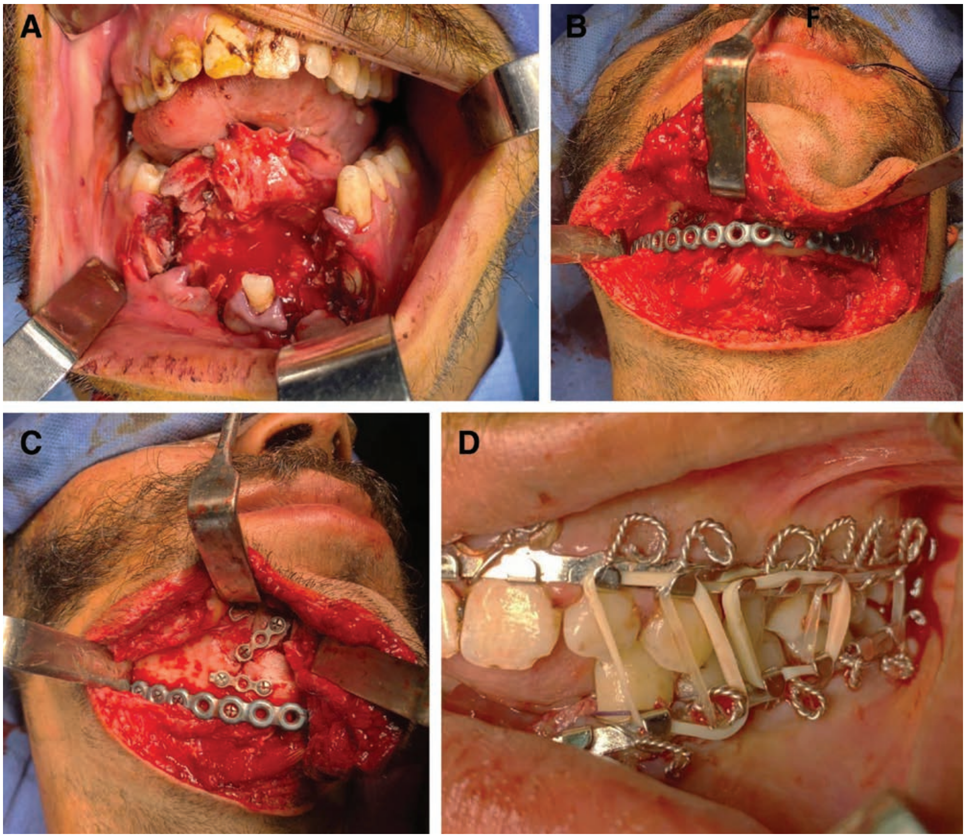

Fig. 2. Gunshot patient. A, Intraoral photograph exhibiting the result of a gunshot injury to the mandible. Notice the extensive damage to the bone and alveolar region of the anterior mandible. B and C, Reduction using the prebended reconstruction plate. D, Occlusion was maintained using MMF.

Reconstruction plates used for the rigid fixation were acquired from DePuy Synthes (Johnson & Johnson, West Chester, Pa.).

RESULTS

The characteristics of the five patients are presented in Table 1. We will further present two of the cases.

The first patient, who presented with a comminuted mandible resulting from a GSW also had multiple orthopedic injuries and was taken to the operating room directly from the trauma room following initial assessment (Figs 1–3). Orthopedic surgery was planned for 3–4 hours, following which our surgery began. During this time period, we segmented the CT of the lower jaw and transferred the generated STL file to Geomagic Freeform (Fig. 1A). In the Freeform software, virtual reduction of the fragments was performed (Fig. 1B). [**See Video (online)**, which displays the virtual reduction of the comminuted

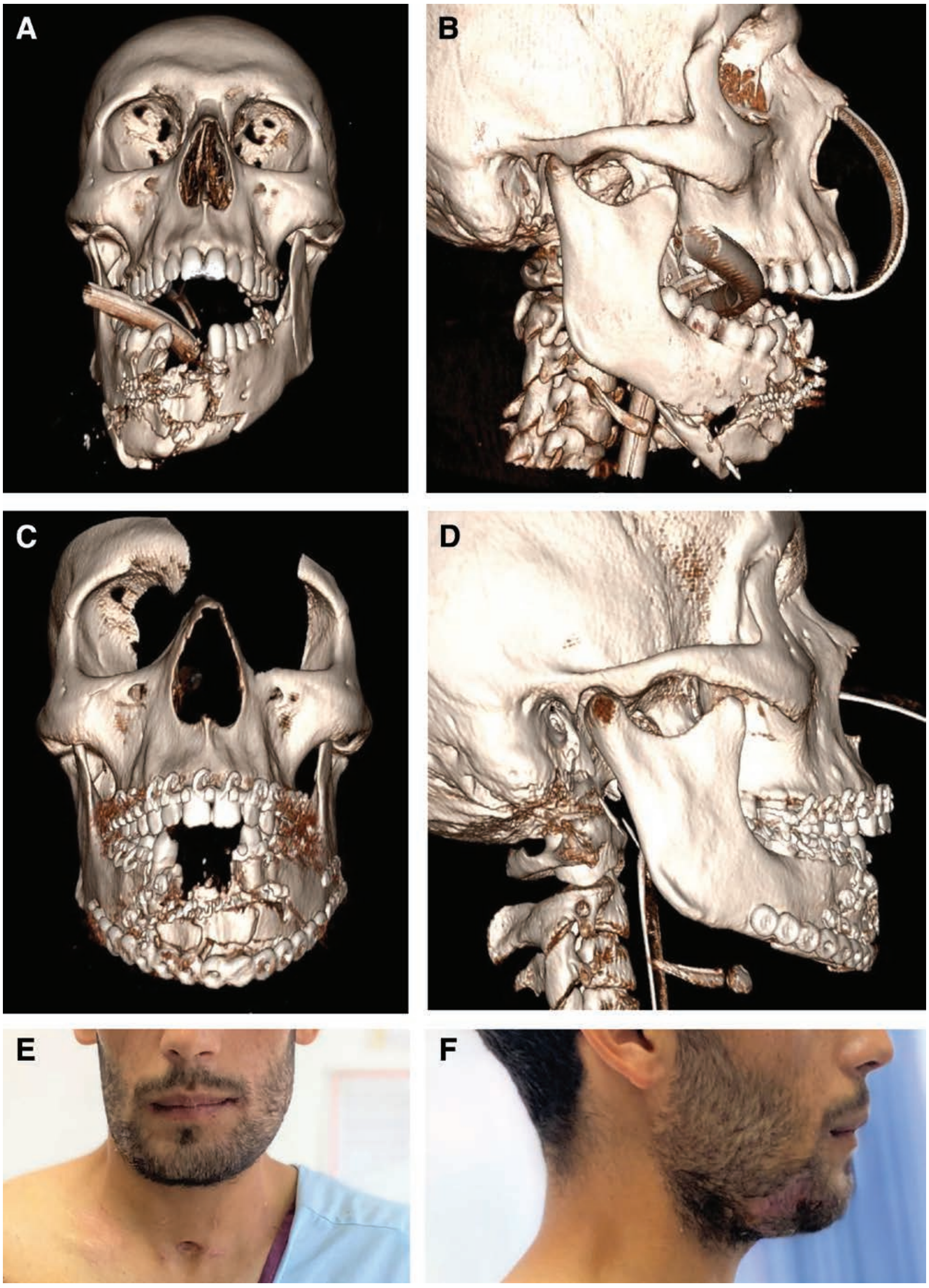

Fig. 3. Imaging and final outcome. A-B, Different views showing the 3D reconstruction of the preoperative CT. C-D, Postoperative CT showing the proper reduction and fixation. E-F, Clinical postoperative photographs showing a good aesthetic result.

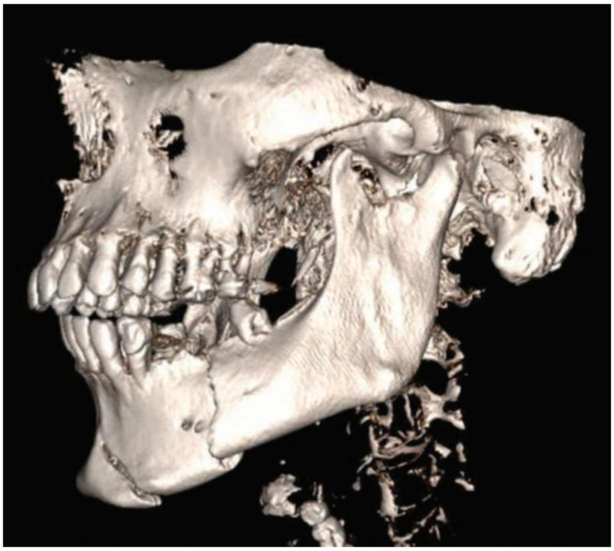

Fig. 4. A case with a fragmented mandible. Radiographic 3D reconstruction of the fractured mandible.

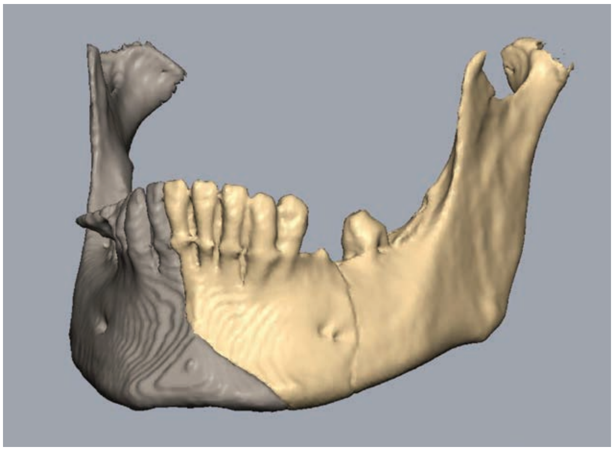

Fig. 5. Three-dimensional planning. The fragmented mandible in the Freeform software following segmentation and reduction of the fragments.

fracture described in Figs. 1–3.] Next, the newly formed mandible was printed using an FDM printer together with a template for repositioning the fragments (Fig. 1C). The last step of preoperative preparation included the adaptation of a reconstruction plate to the printed mandible (Fig. 1D). Figure 2 shows the defect, fixation of the reconstruction plate to the proximal nonfragmented mandibular stumps, which fitted perfectly, and the reduction of the free bone fragments to the reconstruction plate and to one another using miniplates. Figure 2D shows the posterior occlusion. Pre- and postoperative CT imaging are observed in Figure 3. Clinical photographs after 10 days postoperative are presented in Figure 3.

A second patient presented to the emergency room following trauma induced injuries due to a collision with a multirotor drone. The patient underwent surgery 24 hours following arrival. During this period, the same process of segmentation, reduction and reconstruction plate adaptation was performed as detailed before. Figure 4 presents the preoperative mandibular fractures. Figure 5 exhibits the reconstructed mandible. Figure 6A shows the adaptation of the reconstruction plate to the printed mandible. Figure 6B exhibits the accurate reduction and fixation. Postoperative panoramic radiograph shows the accurate reduction and the multiple fracture lines (Fig. 7). To date, all of the patients showed good healing and proper function, and none required a second operation.

DISCUSSION

Comminuted mandibular fractures pose a challenge even to the most experienced maxillofacial surgeon. It is known that the severity of the fracture affects the incidence of complications.[18] Thus, it is not uncommon for these cases to undergo more than one surgery for the achievement of proper reduction. Improper initial management of fractures can lead to significant long-term morbidity (Fig. 8).

With the development of the internal rigid fixation systems, the gold standard for treating comminuted fractures included internal fixation.[2]

With technological advancements in the field of 3D planning and printing, secondary reconstruction treatments experienced a shift toward patient-specific implants. This allows for superior anatomic compatibility, better

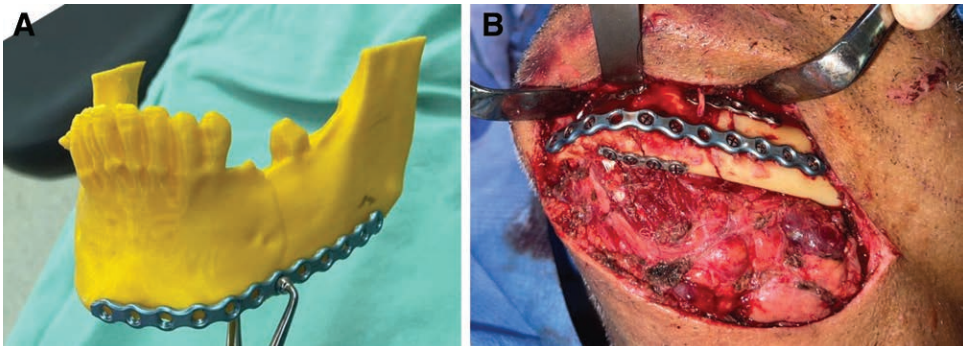

Fig. 6. Three-dimensional printing and adaptation. A, Preoperative adaptation of a reconstruction plate to the reconstructed 3D-printed mandible. B, Following reduction based on the prebended plate.

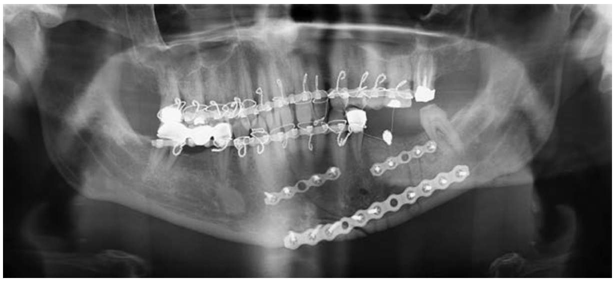

Fig. 7. Panoramic radiograph showing the postoperative result.

Fig. 8. A GSW case treated by conventional intraoperative adaptation of plates resulting in functional disturbances. The postoperative lateral cephalometric radiograph is presented. Notice the inability to properly close the mouth.

aesthetic results, and reduction in operation duration.[11,12] To date, the treatment of primary comminuted fractures, which would benefit the most from this technology, is still not practical. Here, we suggest using this technology in a different way, which allows its integration early during primary treatment.

In this report, we showed the application of this protocol in five cases of comminuted mandibular fractures, we demonstrate two different types of cases, one following a GSW and one following traumatic injury from a drone. In all cases, fragments were reduced using 3D virtual planning software, and the newly created mandible was 3D printed. MMF was performed as the first stage. Following adaptation of the reconstruction plate to the printed reconstructed mandible, the plate was fixed to the noncomminuted remnants of the mandible, and the fragments were reduced according to the reconstruction plate, which served as the template. This manner of reduction and fixation resulted in all cases as a quick and simple process on the one hand, and very accurate on the other hand. The accurate repositioning and closely attached fragments result in a superior and faster healing process, better aesthetic and functional result, and quicker return to normal function with a lower chance for nonunion/malunion or infection. In addition, this method results in shorter operation duration as a result of both sparing the need for intraoperative manipulation of the plate and easier reduction of the fragments. Another advantage is less manipulation of the reconstruction plate because the adaptation is much easier on the model than on the patient. This results in less effects on the integrity of the plate.

As opposed to oncological cases, where resection of bone and fixation of the remaining segments together is required, in the case of a comminuted fracture we need to manipulate and reconstruct the bone using the subsequent fragments. In oncological cases one needs to decide the borders of the resection. Because the manipulation is not performed yet, you still have the correct anatomic position of the remaining fragments for plate adaptation before surgery. Whereas in comminuted fractures we do not have the correct anatomic position and need to virtually reconstruct it before printing the bone. This means that the knowledge and experience of the surgeon/planner is very important in cases of comminuted fractures as opposed to oncological cases.

The software used in our institute are user-friendly, which is very important to integrate the technology for in-house application. Another important aspect in primary treatment setup is making sure this protocol is not time-consuming. With the proper medically affiliated software, the planning aspect should not take more than an hour. Regarding the printing process, this is printer-dependent. It usually can be adjusted with experience, either in the technical aspect (printing speed, base under or around the object and supports) or by minimizing the area of interest to be printed.

CONCLUSIONS

The future consists of real-time treatment with titanium-based patient-specific implants for trauma patients leading to superior functional and aesthetic results, yet, nowadays, the proper setup is absent in the absolute majority of medical centers due to costs, difficulty of maintenance, and the need for professional personnel. Having said that, a stereolithographic or FDM printer is affordable, in our case good quality printers, one of each technology at a price of $3000 each. As for consumables, the price is very low, a few dollars for printing a mandible. These printers do not require professional maintenance and, together with user-friendly 3D virtual planning software, allow for achieving very good results in the treatment of comminuted fractures. This report explains the process in cases of mandibular comminuted fractures, yet this technology can be applied to most fractures and can be a very useful treatment option in the surgeon's toolbox.

Dekel Shilo, DMD, PhD
Department of Oral and Maxillofacial Surgery
Rambam Health Care Campus
8 Ha'Aliyah Street
Haifa 35254
Israel
E-mail: dekelshi@yahoo.com

DISCLOSURE

The authors have no financial interest to declare in relation to the content of this article.

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