

Contribution of Virtual Surgical Planning, Computer-Aided Design, and Computer-Aided Manufacturing to Delayed Mandibular Reconstruction

Halil Ibrahim Canter, Kemalettin Yildiz¹, Kahraman Berkhan Yilmaz², Muhtar Gurol³, Mehmet Veli Karaaltin⁴, Ahmet Kirazoglu¹, Ethem Guneren¹, Mustafa Engin Cakmakci⁵, Majid Ismayilzade

Department of Plastic, Reconstructive and Aesthetic Surgery, Istinye University Faculty of Medicine, ¹Department of Plastic, Reconstructive and Aesthetic Surgery, School of Medicine, Bezmialem Vakif University, ²Department of Plastic, Reconstructive and Aesthetic Surgery, School of Medicine, Acibadem University, ⁴Private Practitioner in Karaaltin Clinic, ⁵Department of Ear Nose Throat, Acibadem Health Care Group, Bakirkoy Hospital, Istanbul, ³Department of Oral and Maxillofacial Surgery, School of Dentistry, Cankiri Karatekin University, Cankiri, Turkey

Abstract

Purpose: Achievement of the correct alignment of malpositioned mandibular segments with displaced condyles and soft-tissue contraction is relatively challenging in patients requiring secondary mandibular reconstruction. The aim of this study was to demonstrate the utility of virtual surgical planning (VSP) and forward engineering with computer-aided design (CAD)/computer-aided manufacturing (CAM) technology in late secondary mandibular reconstruction. **Patients and Methods:** The study sample included 14 patients aged 18–74 years and treated between 2012 and 2017 using secondary segmental mandibular reconstruction. VSP was used for precise condylar location in each mandibular segment, and cutting guides enabled forward engineering in cases treated with vascularized fibular bone grafts. Rapid medical prototyping of the mandible and/or CAD/CAM of temporary fixation guides were used in the remainder of cases for forward engineering purposes. **Results:** VSP and CAD/CAM technology reduced the amount of bone removed for reconstruction, decreased surgical time, increased intraoperative precision, and improved postoperative functional and esthetic outcomes. **Conclusions:** VSP allows seamless secondary mandibular reconstruction with fibular free tissue transfer, and utilization of combinations of mandibular and fibular cutting guides or temporary fixation templates allows for precise and efficient surgical reconstruction through forward engineering. Rapid medical prototyping of custom-made temporary mandibular fixation apparatus can be an alternative method for situations where the cutting guides and permanent fixation plates cannot be manufactured or where free fibular transfer is not the preferred treatment option.

Keywords: Computer-aided design/computer-aided manufacturing technology, secondary mandibular reconstruction, virtual surgery

INTRODUCTION

Mandibular reconstruction using a vascularized fibular free flap after composite resection of tumors is currently a standard treatment option.^[1,2] The increasing esthetic expectations of patients undergoing reconstructive mandibular surgery leave little room for error, motivating reconstructive surgeons to opt for virtual planning and three-dimensional printing technologies to improve outcomes in their patients.^[3-6] Virtual surgical planning (VSP) and computer-aided design (CAD)/computer-aided manufacturing (CAM) technology ensure more predictable results for patients undergoing orthognathic surgery or reconstructive mandibular surgery.^[7]

However, secondary or delayed reconstructions are associated with increased clinical complications as the remnants of the free-floating mandibular segments may have already been displaced, rotated from their original positions, or become

Address for correspondence: Dr. Majid Ismayilzade, Department of Plastic and Reconstructive and Aesthetic Surgery, Faculty of Medicine, Istinye University, Istanbul, Turkey. E-mail: mecidismayilzade@hotmail.com

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malpositioned with inappropriate condylar arrangement, leading to malocclusion, temporomandibular joint (TMJ) dislocation/dysfunction, mandibular asymmetry, and midline shift.^[8,9] In addition, the presence of soft tissue contractures may cause replacement of mandibular segments to the original sites, which may result in miscalculation of the quantity and dimensions of the bone graft required for the bone gap. Mandibular reconstruction demands a high degree of precision due to the spatial and functional constraints of the mandible, and achieving high levels of accuracy (as seen in orthognathic surgeries) in secondary/late cases become increasingly difficult without the inclusion of some sort of simulation surgical techniques.

This study presents our evolving technique for secondary mandibular reconstruction wherein surgical procedures are carried out based on the preoperative data produced by forward engineering with the help of VSP and CAD/CAM technology. The most substantial contribution of this technique to delayed mandibular reconstruction is postsurgical spatial relocation of the condyles bilaterally into their correct locations in the glenoid fossae through precise intraoperative positioning of the residual mandibular segments and fibular free flap/bone grafts.

PATIENTS AND METHODS

Fourteen adult patients (8 males and 6 females; mean age: 39.3 years; range: 18–74 years) requiring mandibular reconstruction for bone defects with varying etiology (e.g., tumor ablative surgery, traumatic bone defects due to accidents, or gun-shut wounds) underwent computer-assisted mandibular reconstruction surgery using VSP and CAD/CAM technology between February 2012 and September 2017. The principles outlined in the Declaration of Helsinki (and later revisions) have been followed and conducted in compliance with good clinical practice. All subjects signed informed consent for the procedures and also for their photographs to be used in this study. Fibular free flaps were used in 11 cases, autologous bone grafting combined with demineralized bone matrix and cancellous allografts were used in two cases, and allografts enriched with mesenchymal stem cells were used in one case. Double-free flaps (free osteocutaneous fibular flaps along with radial forearm flaps) were used in two cases due to the presence of extensive soft-tissue defects on the skin and mucosa. Partial free flap failure (where the intraoral skin island was lost) occurred in one case, and the reconstructed mandibular bony structures were salvaged using a pedicled latissimus dorsi flap.

Computer-assisted mandibular reconstruction was done in three steps, as follows: (1) VSP; (2) design and production of the customized surgical guides and implants utilizing CAD/CAM, 3D printing, and additive manufacturing with laser melting technologies; and (3) surgery.

Virtual surgical planning

A high-resolution computed tomography (CT) scan of the patient's craniofacial skeleton and fibula was obtained before surgery using a multidetector CT scanner (Somatom

Definition, Siemens, Erlangen, Germany). The acquired Digital Imaging and Communications in Medicine format data were then converted into the three-dimensional models of the maxillofacial skeleton utilizing both automatic and manual segmentation techniques on the Mimics Innovation Suite software (Materialise NV, Leuven, Belgium). Thereafter, a virtual surgery planning session was held between the surgeon (first author) and the service providers responsible for design and manufacturing of the implants and cutting guides. Initially, the larger segment of the mandible was repositioned according to the location of the condyle and the remaining upper and lower teeth. A mirror image was created for the fabrication of a phantom mandible, and the accuracy was checked thereafter by virtual inspection of the condyle on the contralateral side and simulation of mandibular movements (mouth opening and closing) on the rotational axis passing through the condyles bilaterally [Supplementary Video 1 shows the simulated rotational movements of the virtual mandible on the rotational axis]. Thereafter, the smaller segments on the contralateral side were transposed onto the silhouette of the phantom mandible to allow determination of the real size of the mandibular defect requiring reconstruction. Trimming of the irregular edges of the mandibular segments and fitting of the fibular bone segment (of the free flap) or the bone graft in the mandibular defect such that the edges of the transferred bone were in line with the corresponding edges of the mandibular margins in all three axes were planned [Figure 1].

Design and production of the customized surgical guides and implants utilizing computer-aided design/computer-aided manufacturing, 3D printing, and additive manufacturing with laser melting technologies

The cutting guides for the mandibular margins and the fibular or bone grafts as well as the stainless steel fixation plates and/or custom-made titanium reconstructive plates were designed using the Mimics Innovation Suite, 3-matic software (Materialise NV, Leuven, Belgium). CAD, 3D printing, and additive manufacturing with laser melting techniques have been utilized for the design and manufacturing of customized surgical guides (Concept Laser Mlab, Germany) and implants (Concept Laser M2, Germany). The accuracy and suitability of the CAD materials were approved by the surgeon in another virtual meeting. In addition, they were also tested on stereolithographic models and printed in accordance with the preoperative data and virtual plan using the Z Printer 510 and 650, USA. Finally, finite element analysis was done to test the durability of all custom-made titanium reconstructive plates retained as implants in the patient.

One patient exhibited tumor recurrence in the resected mandible, and double-cutting sites were designed for both sides of the mandibular segments to allow a repeat osteotomy in case of tumor-free margins which could not be achieved in the first attempt. Similarly, double-cutting sites were also planned for both edges of the fibular cutting guide for this particular patient [Figure 2].

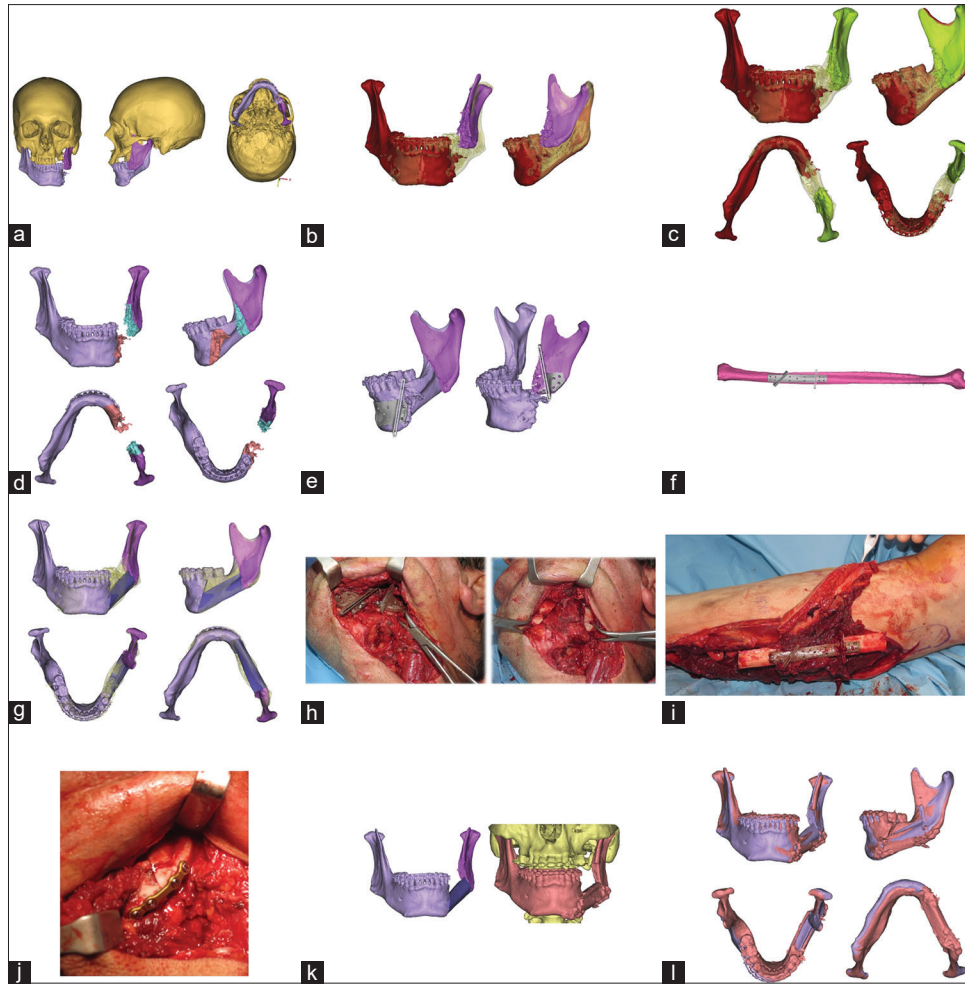


Figure 1: (a) Preoperative frontal, right lateral, and basilar surface render views of the maxillofacial skeleton of the patient with bone defect of the left mandibular corpus. (b) The right mandibular segment was brought in the correct occlusal plane by correct alignment of the upper and lower molar teeth and the central incisive teeth, and then, the color of it is changed into red. Transparent phantom left mandible demonstrated in yellow was created by mirror imaging of the red right mandible according to the imaginary plane passing at the midline of the skull. (c) This phantom mandible is then used as a template to guide the correct positioning of the left mandibular segment, whose color was changed to bright yellow then. (d) Planning of the trimming process at the mandibular edges to create proper smooth contact surfaces with that of fibular graft. (e) Planning of the cutting guides for trimming of those mandibular edges, (f) Planning of the cutting guide for fibula to create maximum contact surfaces with that of trimmed mandibular edges on both sides. (g) Demonstration of the osteotomized fibular bone graft (shown in dark blue) in between the trimmed mandibular segments. The lower border of the fibular graft was adjusted according to the lower border of the phantom mandible. The osteotomized fibular segment fit precisely to both the mandibular defect and the contour of the phantom mandible. (h) Intraoperative views of mandibular segments with applied cutting guides and after osteotomies completed. (i) Intraoperative views of the fibular flap prepared for free tissue transfer with its skin island and with applied cutting guide on before the osteotomies were done. (j) Perfect tridimensional surface fitting between the mandibular and fibular segments, (k) Preoperative planning on the left side and postoperative result on the right side, (l) Superimposition of the preoperative plan and the postoperative results of the patients

Surgery

Patients requiring free flaps were operated upon using a two-team approach, with one at the head-and-neck region exploring the mandible and preparing the recipient vessels for free tissue transfer and the other responsible for harvesting the fibular free flap. The adaptive osteotomies on the harvested fibular grafts and the edges of the mandibular segments were done by the first author in accordance with the preoperative cutting guides.

None of the patients exhibited postoperative maxillomandibular fixation, and oral feeding with clear diet was initiated within

a few days after the operation. The patients were discharged from the hospital after 10–14 days. Moreover, the postoperative follow-up period was 6 months at least to be ensured that no surgical area-related complication was encountered.

Postoperative high-resolution CT scans of the patients were obtained using the same protocol utilized during preoperative scanning.

RESULTS

One patient exhibited partial flap failure due to wound infection, and the reconstructed mandibular bony structures

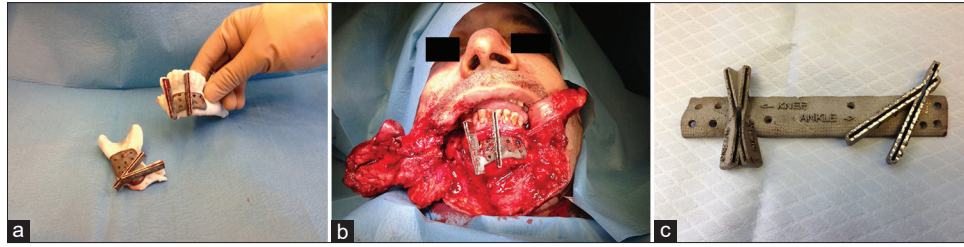


Figure 2: (a) The application of multilevel cutting guides on the right and left mandibular edges of stereolithographic models of a patient with a history of malignancy. (b) Intraoperative views of the left mandibular segment with applied cutting guide on. (c) Multilevel cutting guide for fibula flap. Knee and ankle sites were marked to increase the intraoperative accuracy and orientation

were salvaged using a pedicled latissimus dorsi flap and transferred bone tissue was healed as a bone graft.

Superimposition of the preoperative plan and postoperative outcomes using fusion image registration techniques showed good matching between the two in all patients except one. Postoperative malocclusion due to condylar displacement on the one side was observed in the patient that did not exhibit good matching, and this was corrected by means of a revision surgery with open reduction of the condyle and no revision of the mandibular and fibular segments fixed with custom-made titanium reconstructive plates.

DISCUSSION

The majority of evidence on mandibular reconstruction is based on orthognathic surgeries. Maintenance of double jaw integrity during and, most importantly, after complex orthognathic operations requires precise preoperative planning using a series of intermediate and final splints. Although the planning and operation can be complex, there is little room for error in orthognathic surgery as good results are the only acceptable outcome in patients with high esthetic expectations.^[10]

The key aim of maxillofacial surgery, maintenance of a proper occlusal relationship between the maxilla and mandible along with smooth TMJ movement, is often extremely difficult to achieve in problematic delayed mandibular reconstruction cases due to the inadequacies of the conventional preoperative surgical planning techniques. The presence of complex distorted spatial mandibular anatomy and contracted soft-tissue covers in delayed mandibular cases demands sophisticated preoperative planning techniques to achieve the level of precision seen in orthognathic surgery.^[11,12]

The study hypothesis was that utilizing VSP and CAD/CAM technology for forward engineering during the preoperative period would allow alignment of the edges of the transferred bone perfectly with the margins of the defective mandible, thus facilitating re-orientation of the displaced mandibular segments back into their original positions and also spatial relocation of the displaced condylar heads in the glenoid fossae within the margins of precision identified during orthognathic surgical planning.

CAD/CAM technology represents a new era in craniomaxillofacial surgery by enabling the transfer of

preoperative planning data from the computer to the operating theater (i.e., forward engineering).^[13,14] Moreover, stereolithographic modeling (rapid prototyping), the advantages of which have already been demonstrated in orthognathic surgery, enables handling of real-size skeletal structures preoperatively, thus permitting the performance of model osteotomies, precise bending of the plates, and determination of the location of the screws before commencement of any surgical procedures.^[15]

The majority of challenges associated with secondary mandibular reconstruction can be addressed using computer-aided planning (virtual surgery) and CAD/CAM technology which enables us to create an optimal occlusal relationship between the maxillary and mandibular teeth, thus facilitating reconstruction of the real bone defects instead of what is seen clinically. In addition, occlusal movements during activities such as chewing can be simulated by virtually rotating the planned mandible on the axes passing through the condyles bilaterally, thus permitting forward engineering using CAD/CAM technology. Additive manufacturing with laser melting technologies permits the fabrication of customized surgical guides and implants which, in turn, facilitate effective bone defect filling through perfect alignment of the edges of the bone grafts with the margins of the affected mandible. The displaced mandibular segments can then move into the precise positions planned preoperatively using VSP, thus further improving postoperative functional gain by creating optimal condylar head-glenoid fossa orientation and ameliorating the occlusal relationship. In our study, malocclusion was encountered in one patient who had to undergo open reduction surgery for condylar displacement. Although several factors can be associated with this unfavorable condition, muscular readaptation should be considered while the secondary mandible reconstructions. Muscles adapted to the posttraumatic shape of the mandible may not respond to the corrected axis of mandible immediately. Thus, in the postoperative period, muscle relaxants and/or botulinum toxin injections for a while can be considered as a prophylaxis for condylar displacement.

The technique presented in this study has evolved over time as the incidence of cases has increased. The hypothesis was initially tested using single-segment fibular bone grafts to treat defects in the body of the mandible, following which multisegmented fibular grafts were adapted for more

geometrically complex defects affecting combinations of the symphysis, body, ramus, and condyles of the mandible. Later, permanent implants manufactured using medical grade titanium powder were used to replace fixation guides used temporarily until fixation of the segments using plates and screws was completed. These implants were designed such that their surfaces were in perfect alignment with the bone, as planned using VSP, and the external surfaces were used to achieve better contour restoration and esthetic gain. Finally, permanent custom-made implants in the form of meshed cages filled with bone regenerative tissues (e.g., autografts combined with demineralized bone matrix, cancellous allografts, and vascular stromal fractions obtained from fat tissues) were manufactured.^[16]

The main advantage of this procedure is the reduced adaptation and fixation time required for bony structures which, in turn, decreases the overall surgical time.^[17] Accurate preoperative planning and surgical execution can facilitate merging and fixation of the fibular segments on the permanent implant before they are transferred and fixed with the mandibular edges without the need for measurement of the bone defect.

The potential drawbacks of this technique include longer preoperative time for planning and manufacturing of the implants and increased overall cost of the procedure due to the adjunctive costs of design and prototyping. However, it is also important to bear in mind the potential costs of longer intraoperative duration and increased risk of revision surgery associated with conventional mandibular reconstruction without VSP when considering the overall cost of implant/cutting guide manufacturing.^[18,19] Increasing number of osteotomized bone segments complicates stabilization, even when using fixation guides or implementing prebending of commercial plates on the stereolithographic models, and manufacturing custom-made titanium reconstructive plates (i.e., permanent implants) are the best option for overcoming this.

Additional limitations of this procedure are as follows: (1) the length and the position of the incision and the soft-tissue coverage of the permanent implants must be taken into consideration when designing the implants, cutting guides, and/or fixation guides during the preoperative period and (2) placement of the permanent implants beneath the soft-tissue coverage and lateral displacement of the mandibular segments with bone grafting may create excessive tension on the skin at the incision site or even lead to creation of real soft-tissue defects, particularly in the presence of Andy Gump soft-tissue contractures.

Although virtual planning and CAD/CAM technology are particularly useful for osteotomies of the fibula and mandible due to the associated increase in predictability of outcomes, surgeons should be prepared to operate in a flexible manner taking the necessities of the case into consideration. Prediction of the levels of osteotomy in patients with malignancies or osteoradionecrosis is relatively difficult, and Figure 2 shows

the multilevel cutting guides prepared for such patients. Frozen sections of the trimmed ends of the mandible on both sides were sent for examination to confirm whether the level of resection was tumor free, and further resection was carried out on the one side to create a clear margin. Similarly, multilevel cutting guides must also be prepared for the fibula, and the fibular osteotomies should be postponed until examination of the mandibular frozen sections confirms the amount of residual bone defect on the mandibular site. The surgical team should be ready to adapt in terms of experience, availability of necessary equipment, and ability to perform salvage operations when encountering intraoperative changes in the surgical plan and altered postoperative requirements during the follow-up period.

No postoperative complications associated with implant failure were observed in the current study. However, further investigations evaluating the tolerance of patients to larger titanium implants and studies comparing the mechanical properties of custom-made reconstruction titanium plates/implants to commercially available plates currently used in reconstructive surgery are necessary.

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Conflicts of interest

There are no conflicts of interest.

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