Translating Computer-Aided Design and Surgical Planning Into Successful Mandibular Reconstruction Using a Vascularized Iliac-Crest Flap

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Purpose: This study evaluated the computer-aided approach to the reconstruction of mandibular defects using a vascularized iliac-crest flap.

Materials and Methods: From December 2015 to October 2016, 14 patients (8 men and 6 women) 18 to 64 years old (median age, 29 yr) were treated at the Peking University School and Stomatology Hospital (Beijing, China). Biopsy specimens from all patients were subjected to histologic examination before segmental mandibulectomy. Computer-based surgical techniques, including virtual surgical planning, computer-aided design and manufacturing, rapid prototyping, and intraoperative navigation, were used to restore the anatomic continuity and configuration of the mandible using a vascularized iliac-crest flap. Two transverse dimensions and 1 anteroposterior (A-P) dimension were evaluated based on the virtual plan and postoperative computed tomogram. Lines from condylar head to condylar head and from gonial angle to gonial angle were defined as the transverse dimensions. A perpendicular line drawn from the mandibular midline to the center point on the condylar head to condylar head measurement was defined as the A-P dimension. Complications were evaluated during follow-up.

Results: The flap success rate was 92.9% (13 of 14), with 1 flap failure. After the operation, there were no other serious complications in 13 of the 14 patients, who exhibited a good mandibular configuration with good occlusion. Furthermore, the height of bone graft was sufficient for implants. Healing of the recipient and donor sites with no serious complication was uneventful. The average surgical errors in the A-P dimension and transverse dimensions were 1.8 ± 1.0 mm (range, 0.2 to 3.7 mm), 2.2 ± 1.1 mm (range, 0.9 to 5.0 mm), and 2.6 ± 1.6 mm (range, 0.3 to 7.2 mm), respectively.

Conclusions: The use of these digital techniques was found to be a viable option for reconstruction of mandibular defects, but the results should be interpreted cautiously because of the small number of patients and the relatively short follow-up.

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Mandibular reconstruction is one of the cornerstones of oral and maxillofacial surgery because of the mandible's esthetic importance and its central role in speech, swallowing, and chewing—with the help of prosthetics.[1-3] Bone grafting is a good option for such reconstructions, but functional and esthetic outcomes are strongly influenced by the position and shape of the graft.

Since Hidalgo[4,5] introduced the free fibular flap, it has become the standard for reconstructions of osseous defects in the maxillofacial area. However, in dentate patients, the gracile fibula bone produces an asymmetric facial appearance and inappropriate load situations. The iliac-crest flap, because of its shape and height, has recently emerged as a good option for mandibular reconstruction.[2,6]

To achieve satisfactory reconstruction, some surgeons generate 3-dimensional (3D) digital reconstructions from computed tomographic (CT) scans and then use surgical simulations to optimize and plan the procedures required to make the reconstruction a reality. Successful translation of this plan in the operating room is achieved with the aid of cutting guides and pre-bent plates. Several workflows have been described for fibula graft procedures.[7-9]

For those patients who would benefit from an iliac-crest graft, these digital tools are not widely available. This study investigated whether virtual surgical planning, computer-aided design and manufacturing (CAD/CAM), rapid prototyping, and intraoperative navigation would translate a simulated surgical operation into a real-world mandibular reconstruction using a vascularized iliac-crest flap.

Materials and Methods

PATIENT DETAILS AND DIAGNOSIS

From December 2015 to March 2016, 14 patients (8 men and 6 women) 18 to 64 years old (median age, 29 years) were treated at the Peking University School and Stomatology Hospital (Beijing, China). Biopsy specimens from all patients were subjected to histologic examination before segmental mandibulectomy. Patient characteristics are listed in Table 1. Nine patients had mandibular defect type ramus and body of mandible (RB) and 5 had mandibular defect type body of mandible (B) according to the classification of mandibular defects by Urken[10] after segmental mandibulectomy. Treatment was approved in all cases by the ethical committee of the Peking University School and Hospital of Stomatology. All patients provided written informed consent before their inclusion.

Table 1. PATIENT AND TREATMENT CHARACTERISTICS

Characteristics	
Gender, n	
Men	8
Women	6
Age (yr)	
Median	29
Range	18-64
Histology	
Ameloblastoma	9
Ossifying fibroma	4
Cementoblastoma	1
Defect*	
RB	9
B	5
Length of iliac bone: condyle + ramus + body + symphysis (cm)	
Median	9.5
Range	6-14
Height of iliac bone (cm)	
Median	2.5
Range	2-3
Graft osteotomies	
1	6
2	8
Complications	
Flap failure	1
Mild donor-site pain	2
Sensory deficits	2

Abbreviations: B, body of mandible; RB, ramus and body of mandible.

* Classification of mandibular defects by Urken.

Zheng et al. Computer-Aided Mandibular Reconstruction. J Oral Maxillofac Surg 2018.

DIGITAL RECONSTRUCTION OF DEFECT REGION AND SURGICAL SIMULATION

Preoperative 3D digital reconstruction of the mandible was performed based on preoperative CT scans (1.0-mm slice thickness) of the patient for whom segmental mandibular resection and reconstruction using a vascularized iliac-crest flap was planned. A virtual mandibulectomy was performed with the computer-based planning software package, ProPlan CMF 1.4 (Materialise, Leuven, Belgium), in accordance with the clinical and 3D radiographic findings. Then, the healthy right side of the mandible was mirrored across the midplane to simulate the original healthy shape of the missing left mandibular segment (Fig 1A). A reconstruction plate (AO CMF 2.0-mm mandibular locking plate system; DePuy Synthes, Solothurn, Switzerland) was pre-bent to the contour of the mandible model in the conventional manner (Fig 1B). The reconstructed segment (corresponding to the location of the defect) was separated from the "healthy" part of the model to

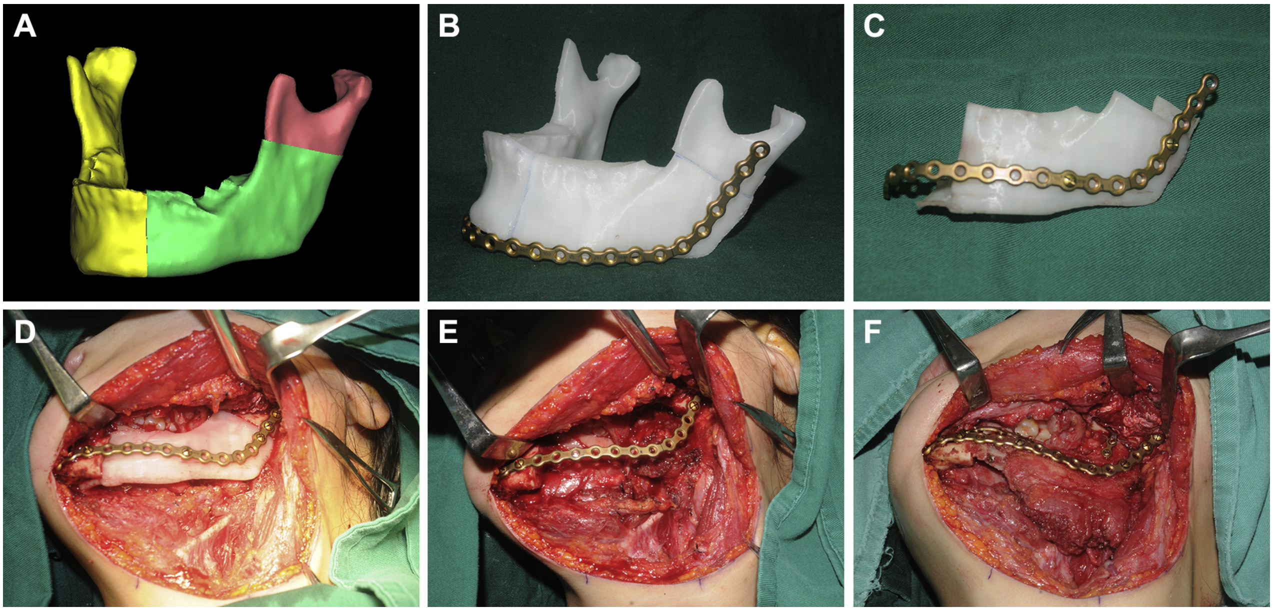

FIGURE 1. *A*, Virtual mandibulectomy and mirror planning by ProPlan CMF. *B*, Rapid prototype model and pre-bent reconstruction plate. *C*, Reconstructed segment (reconstruction model) of a rapid prototype model with bilateral guide wings and a fixed reconstruction plate. *D*, The reconstruction model with the affixed reconstruction plate was inserted precisely with guidance from its bilateral wings and the BrainLAB navigation system. *E*, The reconstruction model was removed, and the reconstruction plate was fixed in position. *F*, The iliac-crest flap was transferred to the recipient site and its 3-dimensional position was confirmed to match the planned position derived from the surgical simulation using BrainLAB navigation.

Zheng et al. Computer-Aided Mandibular Reconstruction. J Oral Maxillofac Surg 2018.

form the "reconstruction model"; guide wings were created at the 2 ends of this model and the reconstruction plate was attached (Fig 1C). The length and shape of the model were measured to improve the efficiency of iliac flap harvesting. Data from the simulation plan generated through ProPlan CMF were imported into the surgical navigation system, BrainLAB iPlan 1.0 (BrainLAB, AG, Feldkirchen, Germany).

SURGICAL PROCEDURE

Under general anesthesia, a precise mandibulectomy was performed under the guidance of the BrainLAB navigation system according to the cutting plan derived from the ProPlan simulation. The mandibulectomy and iliac flap harvesting were performed simultaneously by 2 teams. After the mandibulectomy, the occlusion was fixed by arch bars and the osteotomy site would be reconfirmed by the surgical navigation. Then, the reconstruction stereo model with the affixed reconstruction plate was inserted precisely into the mandibular defect area under the guidance of the BrainLAB system and the bilateral guide wings were matched to the inferior margin of the mandibular body (Fig 1D). Then, the reconstruction model was removed, leaving the reconstruction plate in position. The plate was bicortically fixed to the proximal mandibular segments, thereby bridging the bony defect (Fig 1E).

The harvested iliac flap was shaped according to the dimensions of the reconstruction model and fixed to the remaining mandibular bone under the guidance of BrainLAB. After fixing the grafted bone, it was anastomosed to the recipient-site vessels (Fig 1F).

POSTOPERATIVE EVALUATION

Postoperative CT scanning was performed 3 months after surgery to assess the accuracy of the reconstruction (Fig 2). Two transverse linear measurements and 1 anteroposterior (A-P) linear measurement in the preoperative digital reconstruction plan were compared with the postoperative 3D surgical result to identify whether the planned reconstructive result was achieved, as described by Foley et al.[1] The first transverse measurement was the intercondylar distance, and the second was the intergonial angle distance. The A-P analysis was performed by measuring a perpendicular line drawn from the mandibular midline to the center point of the intercondylar measurement.

The height of the dentate bone graft was evaluated according to the data of the postoperative CT.

Results

All deep circumflex iliac artery (DCIA) flaps were harvested successfully. The overall flap success rate

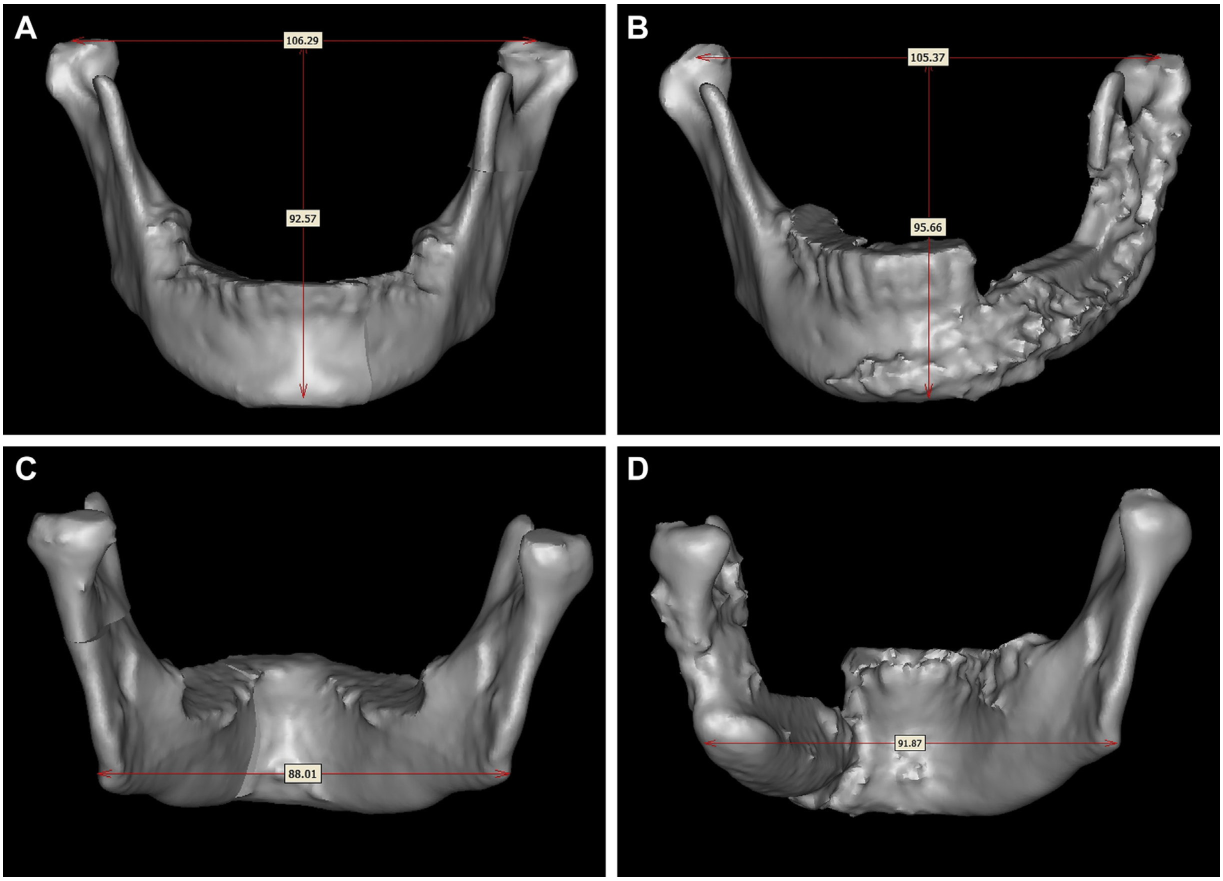

FIGURE 2. *A*, Anteroposterior analysis and intercondylar dimension analysis of the virtual surgical plan. *B*, Intergonial angle dimension analysis of the virtual surgical plan. *C*, Anteroposterior analysis and intercondylar dimension analysis of the actual surgical result. *D*, Intergonial angle dimension analysis of the actual surgical result.

Zheng et al. Computer-Aided Mandibular Reconstruction. J Oral Maxillofac Surg 2018.

was 92.9% (13 of 14), with only 1 flap failure. For the patient with flap failure, free iliac-crest bone grafting was performed as the secondary surgery. Healing of the recipient and donor sites was uneventful. There were no serious donor-site complications, such as such as hernia, bone fracture, and gait disturbance, during the follow-up. However, mild donor-site pain was found in 2 patients and sensory deficits in the distribution of the lateral femoral cutaneous nerve occurred postoperatively in 2 patients, which gradually resolved in 1 patient.

After the operation, all 14 patients exhibited good mandibular configurations with good occlusion (Figs 3, 4). The mean difference in the planned surgical movement from the actual surgical result in the A-P dimension was 1.8 ± 1.0 mm (range, 0.2 to 3.7 mm). The mean differences in the intercondylar and the intergonial angle dimensions were 2.2 ± 1.1 mm (range, 0.9 to 5.0 mm) and 2.6 ± 1.6 mm (range, 0.3 to 7.2 mm), respectively (Table 2).

Furthermore, the height of the dentate bone graft of the patient who received the nonvascularized iliac graft was less than 2 cm because of bone absorption. The heights of the dentate bone graft in the other patients with successful DCIA flaps were greater than 2.5 cm.

Discussion

The mandibulectomy is a good treatment option for tumor in the mandible; however, the surgery creates jaw defects associated with negative functional and esthetic consequences. Mandibular reconstruction is necessary to overcome this problem. The fibula, scapula, and iliac crest are the most commonly chosen donor sites for reconstructing mandibular defects.[1] The bone grafts are fixed to the remaining mandibular bone with the aid of a bridging reconstruction plate or miniplates. Thus, the position of the bone graft is influenced by the dimensions and position of the plate.[7] For mandibular defects, it is often difficult to place the bridging plate correctly and obtain the desired position without any anatomic orientation. The remaining proximal segments of the mandible are in an unstable position, and it is extremely difficult to

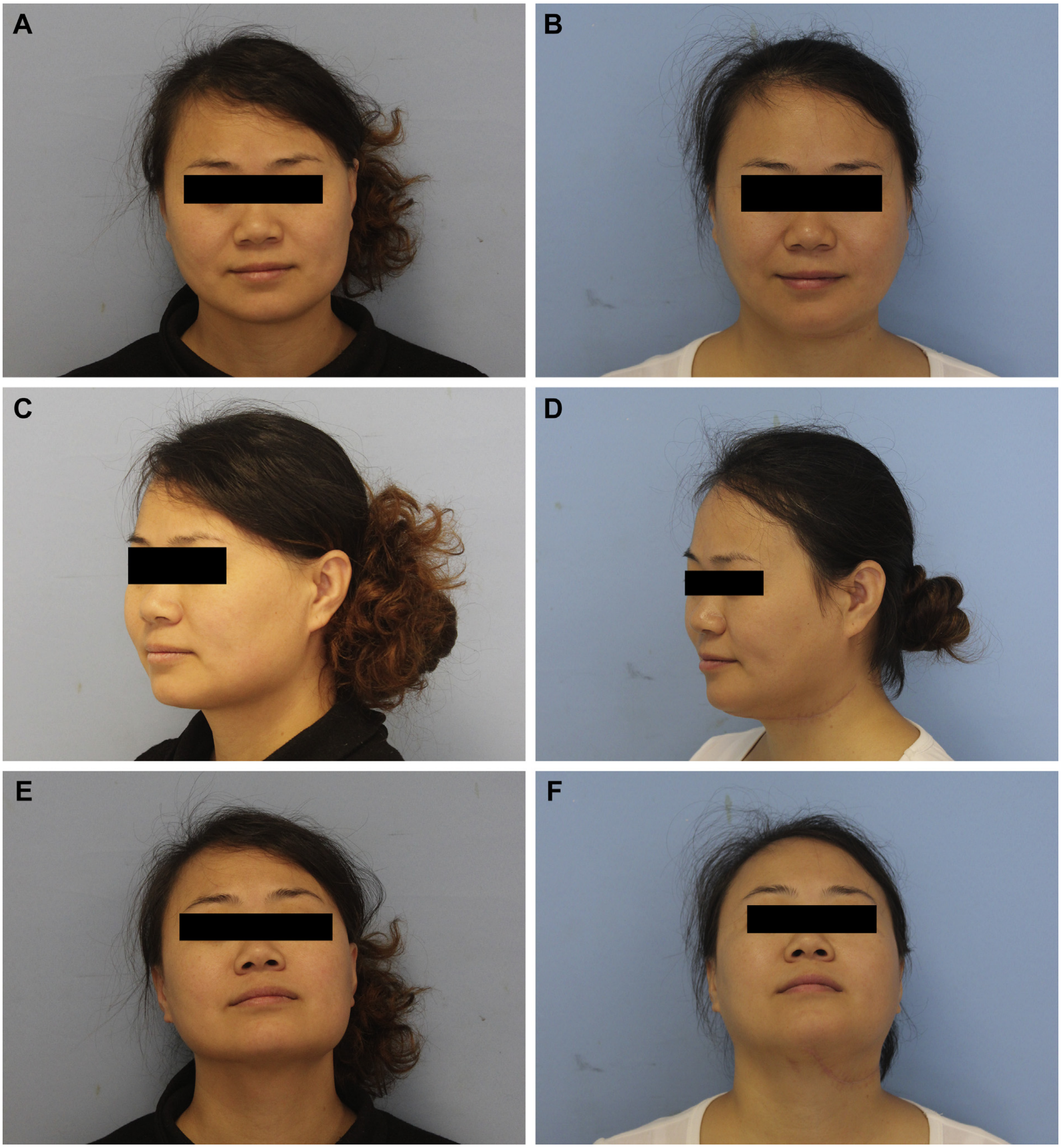

FIGURE 3. Comparison of *A*, *C*, *E*, preoperative and *B*, *D*, *F*, postoperative facial profiles.

Zheng et al. Computer-Aided Mandibular Reconstruction. J Oral Maxillofac Surg 2018.

ascertain the exact 3D configuration of the mandibular defect. Computer-based treatment planning systems allow faster and more precise planning and reconstruction.[8,9] However, such digital techniques are rarely used in mandibular reconstructions using vascularized iliac-crest flaps, and the procedures developed through surgical simulation are often difficult to apply in the real world.

CAD/CAM is the main method for transferring the preoperative surgical simulation to the actual mandibular reconstruction surgery. CAD/CAM resection guides, cutting guides, and pre-bent reconstruction plates were used for mandibular reconstruction.[11-13] These studies reported accurate reconstruction results. However, soft tissue, extensive tumors, and malignancy can affect CAD/CAM resection guides or plates. Specifically, it was difficult to control mandibular mobility and to determine the suitable position of the condyle in the resected side without intermaxillary fixation. The

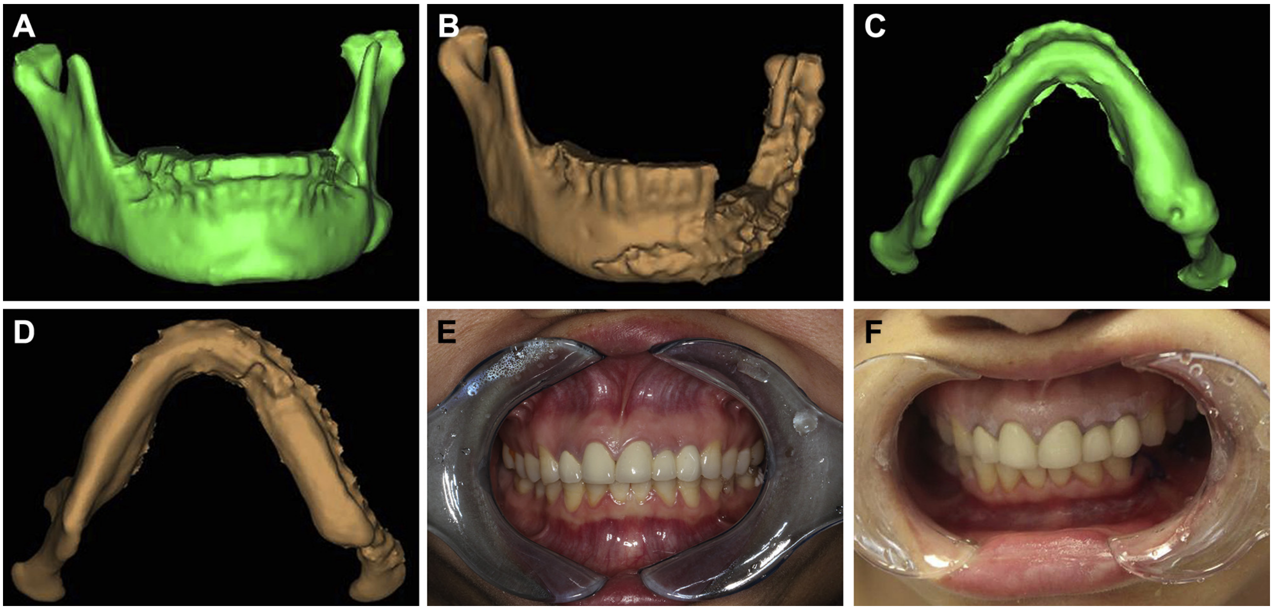

FIGURE 4. *A*, *C*, Preoperative and *B*, *D*, postoperative 3-dimensional views of the mandible. *E*, Preoperative occlusion. *F*, Postoperative occlusion.

Zheng et al. Computer-Aided Mandibular Reconstruction. J Oral Maxillofac Surg 2018.

navigation system is another virtual reality bridge for surgery.[14-18] Yu et al[19] introduced an innovative method to improve the accuracy of mandibular reconstruction with the vascularized iliac-crest flap using computer-assisted techniques. Pre-bending a reconstruction plate on the stereo model of the reconstructed mandible and a navigation system were the main computer-assisted techniques. However, the position of the mandible on the 2 sides can be difficult to control if the defect is larger than 6 cm and involves the body and ramus of the mandible. In the present study, the reconstruction stereo model with the affixed reconstruction plate was used to control mandibular mobility and the surgeons could readily obtain the suitable position of the condyle. Also, the position of the mandible on the 2 sides could be confirmed by surgical navigation. Thus, the surgeons achieved a precise mandibulectomy and accurately inserted the bridging plate at its correct location with the aid of a simulation-derived surgical plan and an intraoperative navigation system. To restore the anatomic continuity and configuration of the mandible, the iliac flap was reshaped based on the reconstruction stereo model and the fixed bridging plate. During the operation, the surgeons only needed to confirm the position of the condyle and the iliac bone by surgical navigation, so this procedure could be less time consuming and more easily compared with the navigation-guided plate positioning procedure, especially for an RB mandible defect larger than 6 cm. Juergens et al[15] used a navigation system to harvest an iliac graft for mandibular reconstruction. Through this method,

Table 2. TRANSVERSE AND A-P MEASUREMENTS (N = 14)

	VSP (mm)	Postoperative (mm)	Difference* (mm)
A-P	101.8 ± 4.5	101.8 ± 4.1	1.8 ± 1.0 (range, 3.5)
Condylar	101.6 ± 2.6	101.6 ± 3.0	2.2 ± 1.1 (range, 4.1)
Gonial angle	89.3 ± 3.7	88.5 ± 4.6	2.6 ± 1.6 (range, 6.9)

Note: Linear measurements of the virtual plan and the actual surgical result from patients who underwent mandibular reconstruction with iliac-crest flaps are presented. Lines from condylar head to condylar head and from gonial angle to gonial angle were defined as the transverse dimensions. A perpendicular line drawn from the mandibular midline to the center point on the condylar head to condylar head measurement was defined as the A-P dimension.

Abbreviations: AP, anteroposterior; VSP, virtual surgical plan.

* Difference = |VSP − postoperative|.

Zheng et al. Computer-Aided Mandibular Reconstruction. J Oral Maxillofac Surg 2018.

the surgeons might identify the ideal donor site inside the iliac bone where the outline and shape are most similar to the missing bone in the mandible. Thus, they could decrease the risk of wasting donor bone and duration of surgery and obtain optimal accuracy. However, this method ignores the fact that the harvested iliac graft must be shaped to fit the configuration of the mandible and the virtual plan cannot be merely transferred to harvest the bone graft. From the harvested bone graft to mandibular reconstruction, there are many procedures that mainly affect accurate mandibular reconstruction. In the present study, the bone graft was harvested according to the reconstruction stereo model, which was based on mirroring across the midplane to simulate the original healthy shape of the missing left mandibular segment. With the help of the reconstruction stereo model with the affixed reconstruction plate and the navigation system, the surgical simulation was straightforward to apply successfully in the actual surgery.

Defined A-P and transverse parameters were applied to investigate the accuracy of mandibular reconstruction.[20] The data indicated that the actual surgical result differed, on average, by only 2.2, 2.6, and 1.8 mm from the preoperative digital reconstruction plan in the 2 transverse and 1 A-P dimensions, respectively. The data of this study seemed less accurate compared with the results of Foley et al[20] who described mandibular reconstruction using nonvascularized iliac crest bone grafts (1.6, 1.7, 0.2 mm, respectively). Larger areas of reconstructed mandible, 9 patients with an RB defect, and difficult fixation at the recipient site were the main reasons. The data results of this study did not affect the postoperative mandibular configurations and occlusion. The authors believe that this computer-aided approach offers greater control of A-P and transverse dimensions of the reconstructed mandible using the vascularized iliac-crest flap.

The present computer-aided methodology proved beneficial for mandibular reconstruction using an iliac flap. However, some weaknesses of this study do exist. The first is the size of the patient population. This study presents important preliminary data that will need to be strengthened with future data of more patients. Second, the accumulative systematic errors cannot be ignored, including the navigation registration process and the 3D resin stereo model printed using rapid prototyping techniques. Third, if the defect included the cross-midline of the mandible more than the type RB or B defect, then the 3D resin stereo model of the entire mandible could not be printed using rapid prototyping techniques by the mirror technique. In this case, the virtual deformable mandibular model might be applied.[21] Moreover, although surgical reliability and accuracy were provided by the methodology, the preoperative work required was quite time consuming and had higher total costs than traditional surgery.

In conclusion, the present research proved that the use of computer-assisted methodology for mandibular reconstruction using free iliac-crest flaps is feasible and advantageous, and its advantages also could improve mandibular reconstruction using other bone grafts. However, the findings should be interpreted cautiously because of the small number of patients and the relatively short follow-up.

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References

1. Farwell DG, Futran ND: Oromandibular reconstruction. Facial Plast Surg 16:115, 2000
2. Baker A, McMahon J, Parmar S: Immediate reconstruction of continuity defects of the mandible after tumor surgery. J Oral Maxillofac Surg 59:1333, 2001
3. Schimmele SR: Delayed reconstruction of continuity defects of the mandible after tumor surgery. J Oral Maxillofac Surg 59: 1340, 2001
4. Hidalgo DA: Fibula free flap: A new method of mandible reconstruction. Plast Reconstr Surg 84:71, 1989
5. Hidalgo DA, Pusic AL: Free-flap mandibular reconstruction: A 10-year followup study. Plast Reconstr Surg 110:438, 2002
6. Brown JS, Magennis P, Rogers SN, et al: Trends in head and neck microvascular reconstructive surgery in Liverpool (1992-2001). Br J Oral Maxillofac Surg 44:364, 2006
7. Hallermann W, Olsen S, Bardyn T, et al: A new method for computer-aided operation planning for extensive mandibular reconstruction. Plast Reconstr Surg 117:2431, 2006
8. Hirsch DL, Garfein ES, Christensen AM, et al: Use of computer-aided design and computer-aided manufacturing to produce orthognathically ideal surgical outcomes: A paradigm shift in head and neck reconstruction. J Oral Maxillofac Surg 67:2115, 2009
9. Roser SM, Ramachandra S, Blair H, et al: The accuracy of virtual surgical planning in free fibula mandibular reconstruction: Comparison of planned and final results. J Oral Maxillofac Surg 68: 2824, 2010
10. Urken ML, Weinberg H, Vickery C, et al: Oromandibular reconstruction using microvascular composite free flaps. Report of 71 cases and a new classification scheme for bony, soft-tissue, and neurologic defects. Arch Otolaryngol Head Neck Surg 117:733, 1991
11. Leiggener C, Messo E, Thor A, et al: A selective laser sintering guide for transferring a virtual plan to real time surgery in composite mandibular reconstruction with free fibula osseous flaps. Int J Oral Maxillofac Surg 38:187, 2009
12. Dérand P, Hirsch JM: Virtual bending of mandibular reconstruction plates using a computer-aided design. J Oral Maxillofac Surg 67:1640, 2009
13. Ciocca L, Mazzoni S, Fantini M, et al: CAD/CAM guided secondary mandibular reconstruction of a discontinuity defect after ablative cancer surgery. J Craniomaxillofac Surg 40:e511, 2012
14. Shan XF, Chen HM, Liang J, et al: Surgical navigation-assisted mandibular reconstruction with fibula flaps. Int J Oral Maxillofac Surg 45:448, 2016
15. Juergens P, Klug C, Krol Z, et al: Navigation-guided harvesting of autologous iliac crest graft for mandibular reconstruction. J Oral Maxillofac Surg 69:2915, 2011
16. Mazzoni S, Badiali G, Lancellotti L, et al: Simulation-guided navigation: A new approach to improve intraoperative

three-dimensional reproducibility during orthognathic surgery. J Craniofac Surg 21:1698, 2010
17. Pham AM, Rafii AA, Metzger MC, et al: Computer modeling and intraoperative navigation in maxillofacial surgery. Otolaryng Head Neck 137:624, 2007
18. Beumer HW, Puscas L: Computer modeling and navigation in maxillofacial surgery. Curr Opin Otolaryngol Head Neck Surg 17:270, 2009
19. Yu Y, Zhang WB, Wang Y, et al: A revised approach for mandibular reconstruction with the vascularized iliac crest flap using virtual surgical planning and surgical navigation. J Oral Maxillofac Surg 74:1285, 2016
20. Foley BD, Thayer WP, Honeybrook A, et al: Mandibular reconstruction using computer-aided design and computer-aided manufacturing: An analysis of surgical results. J Oral Maxillofac Surg 71:e111, 2013
21. Quan C, Zhigang C, Xin P, et al: Potential new method of design for reconstruction of complicated mandibular defects: A virtual deformable mandibular model. Br J Oral Maxillofac Surg 54:170, 2016