A New Procedure Assisted by Digital Techniques for Secondary Mandibular Reconstruction With Free Fibula Flap

Yao Yu, MD, Wen-Bo Zhang, MD, Xiao-Jing Liu, MD, Chuan-Bin Guo, MD, PhD, Guang-Yan Yu, MD, DDS, and Xin Peng, MD, DDS

Purpose: To describe a new procedure assisted by digital techniques for secondary mandibular reconstruction with free fibula flap.

Methods: The 3-dimensional (3D) reconstruction images for vessels were used to demonstrate the vascular diameter and location, which help select the most suitable vein and artery for anastomosis. Maxillary and mandibular stone models of the patient were fabricated and a stable occlusal relationship was determined on an articulator. The 3D tooth model data were scanned using a 3D-optical measuring system, and the obtained stereolithographic (STL) data were imported to Geomagic software. Preoperative maxillofacial and fibular noncontrast-enhanced computed tomography scans were acquired, and the data were imported to ProPlan CMF software. The maxilla and mandible were segmented, and STL data were imported to Geomagic software. The registration function was used to determine the ideal mandibular position. First, with the maxillary position fixed, the maxillary and mandibular models were registered with the maxilla. Then, with the tooth model positions fixed, the mandible was registered with the models. The STL data for the mandible were imported to ProPlan CMF software. Virtual plan and surgical navigation were used to design and correct the mandibular and fibular position.

Results: Our technique enabled precise recovery of the original mandibular configuration in this patient. The shift in the reconstructed mandible and fibular segment was <5 mm.

Conclusions: The authors described a new procedure for secondary mandibular reconstruction with a free fibular flap using digital techniques involving surgical navigation, which have the potential to improve the clinical outcomes of this procedure.

Key Words: Digital techniques, secondary mandibular reconstruction, surgical navigation

From the Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, Beijing, China.

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Address correspondence and reprint requests to Prof Xin Peng, MD, DDS, Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, 22# Zhongguancun South Avenue, Beijing 100081, China; E-mail: pxpengxin@263.net

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Mandibular reconstruction is considered a challenging procedure in the field of head and neck reconstructive surgery, and it aims to achieve the best possible functional and esthetic outcomes. In 1989, Hidalgo demonstrated the utility of free vascularized fibular flaps for mandibular reconstruction.[1] Since then, the fibular flap has become a highly reliable and popular flap for mandibular reconstruction.[2] This flap provides several advantages, including a long pedicle, a wide vessel diameter, and the ability to incorporate skin, muscle, and bone components, which are required for mandibular reconstruction.[3]

At the time of this writing, the use of computer-assisted techniques for mandibular reconstruction is gaining popularity because of a decrease in the surgical duration and complication rate and improved esthetic and functional outcomes.[4–6] These techniques include the use of 3-dimensional (3D) stereolithographic (STL) models, cutting guides, prebent plates, and preshaped titanium mesh implants, among others.[7–9] The basic essential step in computer-assisted reconstruction is transfer from the virtual preoperative plan to real-time surgery. It has now become possible to import virtual data to a navigation system that is used to provide guidance for accurate and safe placement of hardware or bone grafts, movement of bone segments, tumor resection, and osteotomy designs.

Secondary mandibular reconstruction is a difficult procedure because of soft tissue contracture and bone tissue instability. Soft tissue contracture can increase the difficulty in achieving inset of the fibular flap. Occasionally, combined free flaps and flow-through or chain-link flaps are used as alternative approaches to provide bony and oral linings in the reconstruction of mandibular composite defects, particularly for patients in whom suitable recipient vessels in the facial region cannot be easily identified.[10,11] In addition, for patients with mandibular defects, the remaining mandible is generally removable. However, it is difficult to determine the position of the remaining mandible preoperatively, and this increases the difficulty in achieving inset of the fibular flap and influences the accuracy of mandibular reconstruction. At the time of this writing, 3D STL modeling and virtual plan have been widely applied in the reconstruction of maxillofacial region and have many prominent advantages, such as improving the accuracy of secondary reconstructed surgery and shortening the operation. The essential basic step in computer-assisted reconstruction is transfer from the virtual preoperative plan to real-time surgery. It has now become possible to import virtual data to a navigation system, which is used to provide guidance for the accurate and safe placement of hardware or bone grafts, movement of bone segments, tumor resection, and osteotomy designs. Finally, newly designed, mobile, intraoperative computed tomography (CT) scanners have become available and can be used to confirm the accuracy of reconstruction before patients leave the operating room.[12] Several appliances and studies regarding navigation surgery have focused on the midfacial

FIGURE 1. Preoperative panoramic radiograph and 3-dimensional imagings of the patient show a mandibular defect involving the left mandibular body and ramus.

region.[12,13] Previously, computer-aided navigation was rarely used for mandibular reconstruction because of the mobility of this bone. In this study, the reconstructed occlusal relationship and virtual plan are imported into the surgical navigation system to achieve the better functional and aesthetic outcome.

The purpose of the present study was to describe a new procedure assisted by digital techniques for secondary mandibular reconstruction with free fibula flap.

PATIENTS AND METHODS

A 53-year-old man presented at our institution with visible left-sided facial deformity. He had undergone mandibulectomy without reconstruction, followed by radiation therapy (70 Gy), for squamous cell carcinoma of the tongue 6 years back. A panoramic radiograph and 3D imagings showed a unilateral mandibular defect including the right mandibular body and ramus (Fig. 1). Furthermore, the patient complained of limited opening mouth and poor occlusion because of soft tissue contracture and the mandibular defect (Fig. 2).

FIGURE 2. Preoperative facial views of the patient show mandibular deficiency and disrupted occlusion.

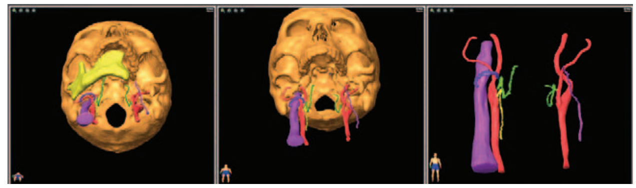

FIGURE 3. Computer tomography angiography findings.

Computer Tomography 3-Dimensional Imaging

Preoperative maxillofacial contrast-enhanced CT data were obtained and imported to iPlan 3.0 software (Brainlab, Feldkirchen, Germany). Bilateral cervical vessels, the mandible, and the maxilla were marked using the navigation software (Fig. 3). The 3D reconstruction images for vessels can clearly demonstrate the vascular diameter and location, which help select the most suitable vein and artery for anastomosis. The right cervical vessels were spared during the previous surgery and radiation therapy. The external jugular vein and external carotid artery, including the lingual artery, could be used for anastomosis.

Occlusal Reconstruction

Maxillary and mandibular stone models of the patient were fabricated and the ideal occlusal relationship was determined by a prosthodontist on an articulator. An occlusal splint was fabricated to fix the ideal occlusal relationship.

Virtual Planning

The stone models fixed by the occlusal splint were scanned by a 3D optical measuring system (Smart Toptics) and STL data were acquired. Then, preoperative maxillofacial and fibular noncontrast-enhanced CT scans with a 1-mm slice thickness were acquired (field of view, 20 cm; pitch, 1.0; slice, 0.75 mm; 120–280 mA). The patient was made to wear a lead–rubber suit to decrease exposure to abdominal radiation. Computed tomography data in the Digital Imaging and Communications in Medicine format were imported to ProPlan CMF software (ProPlan CMF, Materialise NV, Leuven, Belgium). Subsequently, the mandible and maxilla were segmented. Data for the remaining mandible including teeth and the maxilla were separately exported in the STL file format.

The mandibular and maxillary stone models were imported to Geomagic Studio 7 software (Raindrop Geomegic, Durham, NC). The registration function was used to determine the ideal mandibular position. First, with the position of the maxilla fixed, the maxillary and mandibular stone models were registered with the maxilla according to the overlap of the maxillary stone model (Fig. 4). Then, with the position of the maxillary and mandibular stone models fixed, the mandible was registered with the stone models according to the overlap of the mandibular stone model (Fig. 5). Finally, STL data for the mandible, including position data, were imported to ProPlan CMF software.

Using ProPlan CMF software, the osteotomy lines for the mandible moved to the stable position were marked. Mirroring tools were used to form the ideal mandibular contour.[14] According to the ideal mandibular contour, we superimposed the 3D fibular image on the mandibular defect in its desired orientation (Fig. 6). The length of every fibular segment was measured and provided to the surgeon to facilitate intraoperative positioning and placement. The surgeon shaped the fibular flap according to these parameters, cross-checking with a protractor and ruler. Surgical navigation was used to check and correct the shaped fibular segments (Fig. 7). The

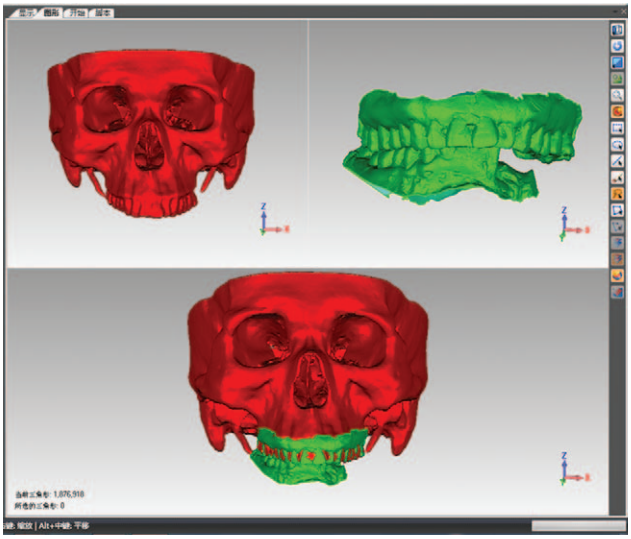

FIGURE 4. Registration between the maxilla and the dentition is completed to confirm the ideal position of the mandibular teeth.

position of the osteotomy lines and relevant parameters regarding the shape of the free fibular flap were also provided to the surgeon.

Navigation Surgery

The entire surgical procedure was guided by the navigation system according to the preoperative virtual plan.

Intraoperative navigation is comparable with GPS systems commonly used in automobiles and comprise 3 primary components: a localizer, which is analogous to a satellite in space; an instrument or surgical probe, which represents the track waves emitted by the GPS unit in the vehicle; and a terminal working station, which is analogous to a road map. The navigation system used in this study was iPlan 3.0 (Brainlab).

Intraoperative navigation was used to implement the virtual plan for mandibulectomy and mandibular reconstruction. The first step of surgery was to secure fixed markers on the patient's head using screws inserted through small incisions in the scalp. The surgeon registered a series of consecutive points over the periorbital and frontal regions using registration equipment known as Z-touch to match the actual maxillofacial skeleton and navigation images on the workstation. To use the navigation process, it was necessary that the mandible be maintained against the maxilla in centric occlusion throughout the navigation process. This could be accomplished by 2 methods. One was to fix the mandible in centric occlusion using an arch bar splint, while the other was to choose 3 distinctive anatomical landmarks on the surface of the remaining mandible and register these points with the virtual image. We used the former method in the present study. An occlusal splint was fabricated to fix the ideal occlusal relationship. Both these techniques facilitate placement of the mandible in the planned position. The available sagittal, coronal, axial, and 3D reconstruction images displayed by the navigation system were used during surgery to accurately determine the osteotomy sites and osteotomy trajectory. Before osteotomy, the occlusion was fixed by the occlusal splint. Under the guidance of a surgical probe, the osteotomy line was marked and the virtual mandibulectomy was transferred to real-time surgery. The osteotomy site was marked using surgical navigation, and a reciprocating saw was used to accomplish the osteotomy. The fibula

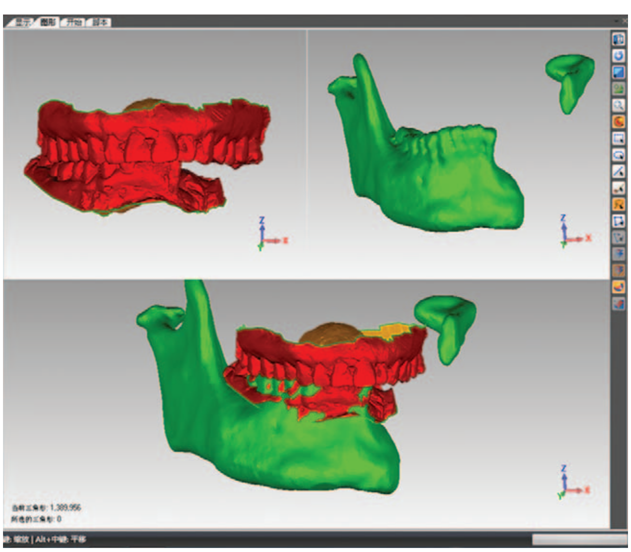

FIGURE 5. Registration between the mandibular teeth and the mandible is completed to confirm the ideal position of the mandible.

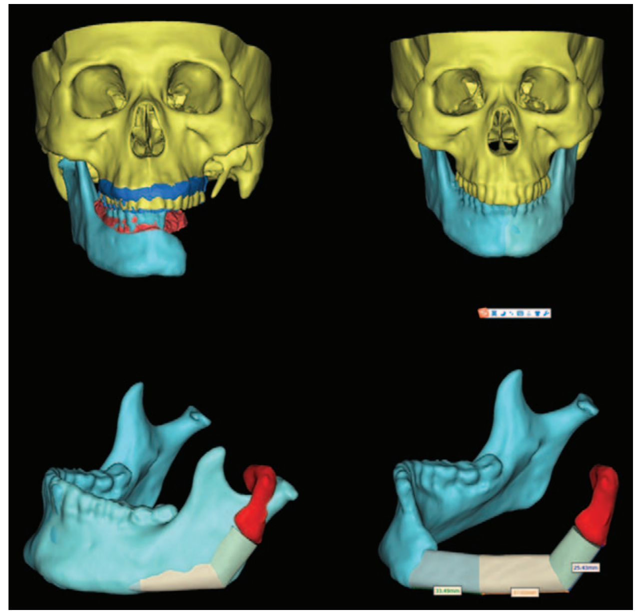

FIGURE 6. Simulation of virtual osteotomy and mandibular reconstruction with a free fibular flap on the Surgicase workstation.

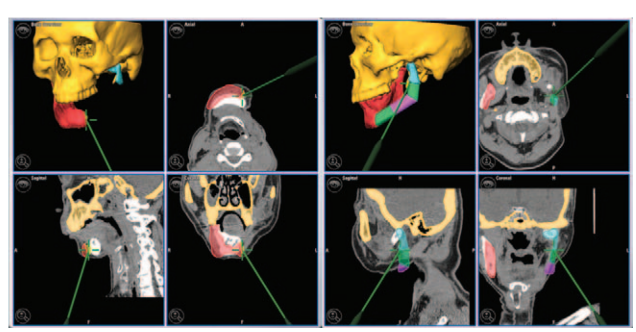

FIGURE 7. The osteotomy line and the position of the fibular segment are verified using surgical navigation.

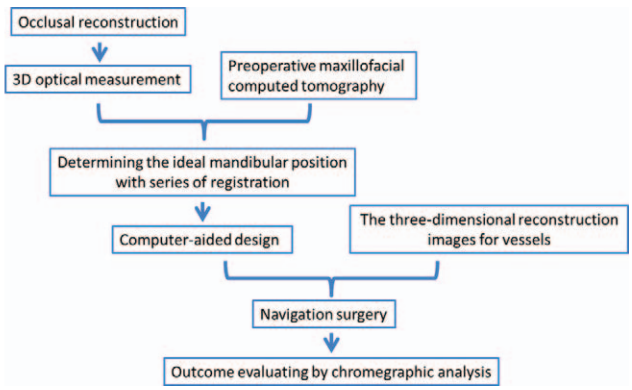

FIGURE 8. Flow diagram for secondary mandibular reconstruction with free fibula flap using digital techniques.

was shaped according to the computer-aided design and recorrected using surgical navigation.

Figure 8 shows a flow diagram for secondary mandibular reconstruction with free fibula flap using digital techniques.

The ethical approval was given for our study. The ethical approval document No. is PKUSSIRB-201522051. This study features human subject, and we confirm that we have read the Helsinki Declaration and have followed the guidelines in this investigation.

RESULTS

The free fibular flaps survived successfully without any complication in this patient. The ipsilateral facial artery and external jugular vein marked on computed tomographic angiography (CTA) images were used for intraoperative anastomosis. The average surgical duration was 440 minutes. The cost of the entire treatment was 2800 RMB (approximately 425 USD), including the cost of the navigation system. The preparation time required before surgery was 2 days more than that for conventional surgery, considering that preparation included CTA, occlusal reconstruction, and virtual planning for navigation.

FIGURE 9. Postoperative 3-dimensional image at 6 months after surgery.

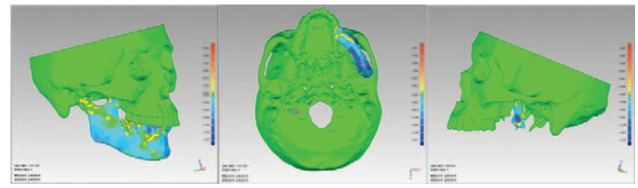

FIGURE 10. Chromatographic analysis of the osteotomy site between every segment of the reconstructed mandible before and after surgery.

Postoperative noncontrast-enhanced CT was performed 6 months after surgery to evaluate the outcomes of mandibular reconstruction (Fig. 9). Chromatography (Geomagic) was used to evaluate the difference between the postoperative and planned mandibular configurations.

We found that the original configuration of the mandible was precisely recovered using our technique in this patient.

For this patient, the average shift in the right mandible with teeth, relative to the preoperative position, was 0.043 ± 0.128 mm. The largest shift on this side was 1.767 mm, while the largest shift of the osteotomy line on this side was 0.905 mm. The corresponding values for the left condyle were 0.007 ± 0.050, 1.787, and 1.194 mm, respectively. The shift in the fibular flap was 0.051 ± 0.196 mm (Fig. 10). At 6 months after surgery, the patient showed a symmetric facial contour, good mastication function, and satisfactory esthetics (Fig. 11).

DISCUSSION

Virtual simulation, based on 3D image planning systems, is used increasingly for preoperative planning of orthognathic surgery. Many studies have already proved that the clinical feasibility of a computer-assisted orthognathic surgical protocol incorporating virtual planning and its transfer to the operating room using computer-aided design/computer-aided manufacture fabricated surgical splints.[15,16] In this study, the ideal mandibular position is determined with series of registrations between teeth stone models and maxillofacial bones. This method is the same as the manufacture of the surgical splints in orthognathic surgery, and it is the first time to apply this method in secondary mandibular reconstruction.

Secondary mandibular reconstruction is a great challenge because of the presence of pathological distortion due to soft tissue scarring and difficulty in locating the position of the remaining mandible before surgery. Previous studies have reported that combined free flaps and flow-through or chain-link flaps are alternative approaches for bone and oral linings in secondary mandibular reconstruction, particularly for patients in whom suitable recipient

FIGURE 11. Facial photographs show a symmetric postoperative facial contour. An intraoral view shows good postoperative outcomes.

vessels in the facial region cannot be identified.[10,11,14] Keles et al[17] define the different courses and percentages of the hepatic artery detected during preoperative evaluation of living liver donors using multidetector CTA. For the patient in this study, who underwent tumor resection without reconstruction, followed by radiation therapy, 3D CT images of blood vessels are acquired to determine the most suitable recipient vessels with regard to position and diameter. Most complications of free fibular flap reconstruction involve vascular compromise. Evaluation of the vascular anatomy provides considerable information that can potentially minimize these complications. Computed tomography angiograph data have been reported to be particularly helpful for secondary free flap reconstruction in the head and neck region after malignant tumor recurrence.[18,19] In these patients, radical neck dissection was performed as part of the first surgery, and several vessels that are commonly used for anastomosis were resected from the root. Visualization of vessels in the head and neck region aid surgeons in selecting suitable vessels for anastomosis and predicting the approximate length of the fibular pedicle, which can prevent the excision of more bone than necessary or the placement of multiple incisions for exposure.

Mastication is one of the most important functions related to the oral and maxillofacial region. Limited mouth opening and disrupted occlusal relationships can impair the quality of life of a patient. In patients with mandibular defects, the range of mouth opening can be obviously improved with the help of secondary mandibular reconstruction and postoperative physical therapy. Occlusal reconstruction is the foundation for this surgery. Appropriate occlusion can aid surgeons in confirming the position of the remaining mandible, while stable occlusion can increase the stability of the mandibular and fibular segments, which is beneficial for the symphysis. In this study, maxillary and mandibular stone models of the patient were fabricated and the ideal occlusal relationship was determined by a prosthodontist on an articulator. An occlusal splint was fabricated to fix the ideal occlusal relationship. Ikawa et al reported a 3D model of the skull and dentition was constructed using CT and 3D laser surface scanning data.[20] Therefore, even if patients exhibit several dental prostheses, the dentition can be precisely superimposed through this technique. The relative position of the maxillary and mandibular teeth was determined by the condylar position and the occlusal relationship.

For secondary mandibular reconstruction, the lack of normal surrounding muscles and skin influences the insertion of the fibula. Because of soft tissue scarring and radiation therapy, it is difficult to decide the ideal position of the remaining mandible solely on the basis of the surgeon's experience. There are 3 possible methods for determining the position of the remaining mandible. The first is to acquire the CT data obtained before the primary surgery. The initial position of the remaining mandible should be recognized as the ideal position to guide fibular placement. The second method involves recovery of the initial mandibular position by occlusal reconstruction. Conventional surgical planning techniques for orthognathic surgery use dental plaster models and acrylic surgical splints to improve the occlusion.[21] Conventional acrylic surgical splints are fabricated from plaster models prepared by pouring improved die stone into polyether impressions. Orthodontic acrylic is stacked onto the occlusal surfaces of teeth to fabricate the splint. Gateno et al stated that conventional plaster model-based surgery will be replaced by computer-assisted surgical planning in the future. Surgical splints will fabricated using computerized software, and the treatment plan will be directly transferred to the patient.[22] Regardless of the type of splint, the 3D position of the proximal mandibular segment containing teeth is confirmed by an ideal occlusal relationship. The degree of precision necessary for secondary mandibular reconstruction is highly dependent on the patient's dentition. The third method is used when initial CT data cannot be acquired and the remaining mandible does not include teeth. The mirror function in ProPlan CMF software is then used to determine the ideal position of the remaining mandible. For the patient in the present study, the position of the right mandible with teeth was determined by occlusal reconstruction.

Computer-assisted surgery is becoming increasingly popular in the field of oral and maxillofacial surgery. In the past, the 3D position of the free fibular flap was very difficult to control, because the procedure was based solely on the surgeon's experience. Therefore, such procedures resulted in occasional disruption of occlusion and unsatisfactory esthetics. However, with the application of virtual technology, mandibular reconstructions are becoming increasingly accurate.[23–25] Virtual planning allows the manipulation of 3D representations of the mandible and the donor site, which can aid surgeons in planning the resection, measuring the defect, and planning the harvesting and contouring of the fibular flap.[26] For secondary mandibular reconstruction, virtual planning is absolutely necessary. The ideal position of the mandibular defect and fibular insertion site is determined by computer-aided design technology. The mirror function in the ProPlan CMF software is used to recover the inferior border of the mandible, while reconstruction of the dentition conforms to the ideal position of the superior border of the mandible.

The guidelines of intraoperative navigation for secondary mandibular reconstruction are as follows. First, stable occlusion should be achieved with occlusal reconstruction. The occlusion before osteotomy should be reproducible after the procedure. Second, the ideal position of the reconstructed mandible with surgical navigation should be reproducible. Navigation for secondary mandibular reconstruction is not feasible for large mandibular defects. For the patient with a large mandibular defect and lacked mandibular teeth, it is difficult to determine the stable occlusion and ideal mandibular position. Furthermore, the mandibular defect was present for a long time, which had led to atrophy of the muscles around the mandible and had compromised the function of the condyle. The ideal mandibular segments verified by navigation were unstable because of muscle imbalance and the requirement for right condylar removal because of tumor recurrence.

Numerous studies have focused on improvements in computer-aided navigation techniques for mandibular reconstruction, with some success. For example, Casap et al[27] compared 2 navigation systems for mandibular reconstruction. The first system, the Image Guided Implantology system (Tom Wilson, Dallas, TX), uses a tooth-mounted sensor frame that is directly attached to the mandible and is specifically designed for implant placement. The navigation error of this system was calculated to be <0.5 mm. The second system, the LandmarkX system (Medtronic, MN), uses a headset frame and requires immobilization of the mandible during surgery. The accuracy of this system was 3 to 4 mm. However, computer-aided navigation is rarely used to reconstruct the mandible because of its mobility. There are 3 possible solutions to this problem. The first is to place the patient in maxillomandibular fixation during CT scanning and surgery; however, this is not feasible for transoral surgery. The second is to place the mandible in centric relation or centric occlusion, either manually or with the help of a dental splint. Although mandibular movements are convenient for surgery, they undermine the accuracy of intraoperative navigation. For secondary mandibular reconstruction in the present study, we chose the second method to overcome the drawbacks related to mobility of the mandible. Before computer-aided navigation, the remaining mandible with teeth in this patient was placed in centric relation using occlusal reconstruction. The third method uses a special sensor frame that is fixed onto the mandible. Because of the synchronization between the sensor frame and the mandible, the surgeon can track the jaw position without increasing the navigation error.

Although this process is time consuming, it has the theoretical advantage of improved accuracy through direct monitoring of the mandibular position, as opposed to monitoring of its position relative to that of other fixed cranial structures.[28] Surgical navigation is a powerful tool that enables the accurate execution of a surgical plan. In secondary mandibular reconstruction, surgical navigation can be used to complete the virtual plan during surgery. In a previous study, the position of the remaining mandible with teeth was determined by occlusal reconstruction and verified by surgical navigation, while the position of the remaining mandible without teeth was confirmed by marked points indicating the position of titanium screws, the result showed that the 3 marked points navigation used for the mandibular reconstruction is reliable and accurate.[29] Because of the limitation of CT accuracy, the surgical navigation was rarely used to adjust the occlusal relationship In this study, several registrations between stone model of teeth and skull in Geomagic software were used to add the reconstructed occlusal relationship to the navigation system. It is the first time to combine occlusal reconstruction and navigation surgery to accomplish the secondary mandibular reconstruction with free fibular flap.

CONCLUSIONS

Mandibular defects resulting from tumor resection and trauma are commonly encountered by oral and maxillofacial surgeons. Secondary mandibular reconstruction is associated with some problems such as the lack of suitable vessels for anastomosis, poor occlusal relationships, and mobility of the remaining mandible. In the present study, we described an effective sequential procedure for secondary mandibular reconstruction with a free fibular flap using virtual planning and surgical navigation, which are expected to improve the clinical outcomes of this procedure.

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