A Revised Approach for Mandibular Reconstruction With the Vascularized Iliac Crest Flap Using Virtual Surgical Planning and Surgical Navigation

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Purpose: The purpose of this study was to describe a revised approach for mandibular reconstruction with vascularized iliac crest flap using virtual surgical planning and surgical navigation.

Patients and Methods: Preoperative maxillofacial and iliac non–contrast-enhanced computed tomography (CT) scans were acquired, and CT data were imported into ProPlan CMF software (Materialise, Leuven, Belgium). We performed virtual mandibulectomy and superimposed the 3-dimensional iliac image on the mandibular defect. The surgeon shaped the iliac flap according to virtual parameters and the stereomodel. Surgical navigation was used to check and correct the shaped segments. The position of the osteotomy lines and relevant parameters regarding the shape of the iliac flap also were provided to the surgeon. After computer simulation, a reconstructed mandibular stereomodel was manufactured. A reconstruction plate was prebent and fixed on this model using titanium screws. The model was scanned, data were imported into ProPlan CMF, the mandible was segmented, and data were imported into the intraoperative navigation system. Then, the model was registered with the original CT data, and the reconstruction plate was eliminated. Navigation data were exported into a universal serial bus drive, which was connected to the terminal working station during surgery. Intraoperative navigation was used to implement the virtual plan for patients. The sagittal, coronal, axial, and 3-dimensional reconstruction images displayed by the navigation system were used to accurately determine the osteotomy sites and osteotomy trajectory during surgery. Surgical probe guidance was used to mark the osteotomy line and transfer the virtual procedure to real-time surgery.

Results: Using our method, we precisely recovered the original configuration of the mandible. The shift in the reconstructed mandible and plate was less than 5 mm.

Conclusions: We provided a new method for mandibular reconstruction with vascularized iliac crest flap and an individual reconstruction plate using computer-assisted techniques involving surgical navigation, which have the potential to improve the clinical outcomes of this procedure.

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Mandibular reconstruction is a challenging procedure in the field of head and neck reconstructive surgery, which aims to achieve the best possible functional and esthetic outcomes. The iliac crest bone graft was used for mandibular reconstruction in the early 20th century.[1] With the development of microvascular surgery, bony reconstruction has been revolutionized because of the application of vascularized bone grafts. The possibility of using vascularized bone flaps led to higher graft survival rates and improved functional outcomes.[2-4] Several different bone flaps have been established over time. Graft selection depends on the defect size and location, requirement for soft tissue, and status of recipient vessels. The microsurgically revascularized iliac crest bone graft has some advantages over other bone grafts, such as the large amount of bone, rich cancellous blood supply, and compact cortex, which make this graft an ideal choice for plate fixation and endosseous implant placement during dental rehabilitation.[5]

Currently, the use of computer-assisted techniques for mandibular reconstruction has increased, leading to a decrease in the surgical duration and complication rate and improved esthetic and functional outcomes.[6-8] These techniques include the use of 3-dimensional (3D) stereolithographic models, cutting guides, prebent plates, and preshaped titanium mesh implants, among others.[9-11] 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 into 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 region.[12,13] Previously, computer-aided navigation was rarely used for mandibular reconstruction because of the mobility of this bone. The purpose of this study was to introduce a revised approach for mandibular reconstruction with the vascularized iliac crest flap using virtual surgical planning and surgical navigation.

Patients and Methods

A 23-year-old female patient came to our institution with visible swelling on the right side of the mandible. A panoramic radiograph showed an extensive, radiolucent, multilocular, expansile lesion (Fig 1). A soft tissue biopsy of the lesion yielded a diagnosis of ameloblastoma.

VIRTUAL PLANNING

Preoperative maxillofacial and iliac non–contrast-enhanced CT scans with a 1-mm slice thickness were acquired, with the former acquired in a stable occlusion position (field of view, 20 cm; pitch, 1.0; slice, 0.75 mm; 120Y280 mA). A lead-rubber suit was used to decrease abdominal radiation exposure. CT data in the Digital Imaging and Communications in Medicine file format were imported into ProPlan CMF software (Materialise, Leuven, Belgium). First, the mandible and maxilla were segmented. Then, we performed virtual mandibulectomy with ProPlan CMF according to clinical and 3D radiologic findings, after which we superimposed the 3D iliac image onto the mandibular defect in its desired orientation according to the ideal mandibular contour (Fig 2). If the contour of the mandible was destroyed by the tumor, mirroring tools were used to form the ideal mandibular contour.[14] The length of every iliac segment was measured and provided to the surgeon to facilitate intraoperative positioning and placement. The surgeon shaped the iliac flap according to these parameters, cross-checking with a protractor and ruler. Surgical navigation was used to check and correct the shaped iliac segments. The position of the osteotomy lines and relevant parameters regarding the shape of the iliac flap also were provided to the surgeon.

After computer simulation was completed by the surgeon and a bioengineer, a reconstructed mandibular and iliac stereomodel was manufactured by the bioengineer using 3D printing technology. A reconstruction plate was prebent and fixed on the reconstructed mandibular model using 2 titanium screws (Fig 3). The iliac crest cutting template was made with silicone rubber to guide the harvest of the iliac crest.

Next, the mandibular model with the reconstruction plate was subjected to CT (field of view, 20 cm; pitch, 1.0; slice, 0.75 mm; 120Y280 mA), and CT data in Digital Imaging and Communications in Medicine file format were imported into ProPlan CMF software. The model was segmented, and data were imported into the intraoperative navigation system (iPlan 3.0; Brainlab, Feldkirchen, Germany). Then, the model was registered with the original CT imaging data, and the image of the reconstruction plate was separated from that of the model using Brainlab software. Six points indicating the positions of the titanium screws were marked to adjust the position of the remaining mandible during surgery (Fig 4). The navigation data were exported into a universal serial bus drive, which was then connected to the terminal working station during surgery.

FIGURE 1. A preoperative panoramic radiograph showed an extensive, radiolucent, multilocular, expansile lesion on the right side of the mandible.

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NAVIGATION SURGERY

The entire surgical procedure was guided by the navigation system according to the preoperative virtual plan. Intraoperative navigation is comparable with global positioning systems commonly used in automobiles and comprises 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 global positioning system 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.

Intraoperative navigation was used to implement the virtual plan for patients undergoing mandibulectomy and mandibular reconstruction. The first step of surgery was to secure fixed markers to 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 (Z-touch; Brainlab) to

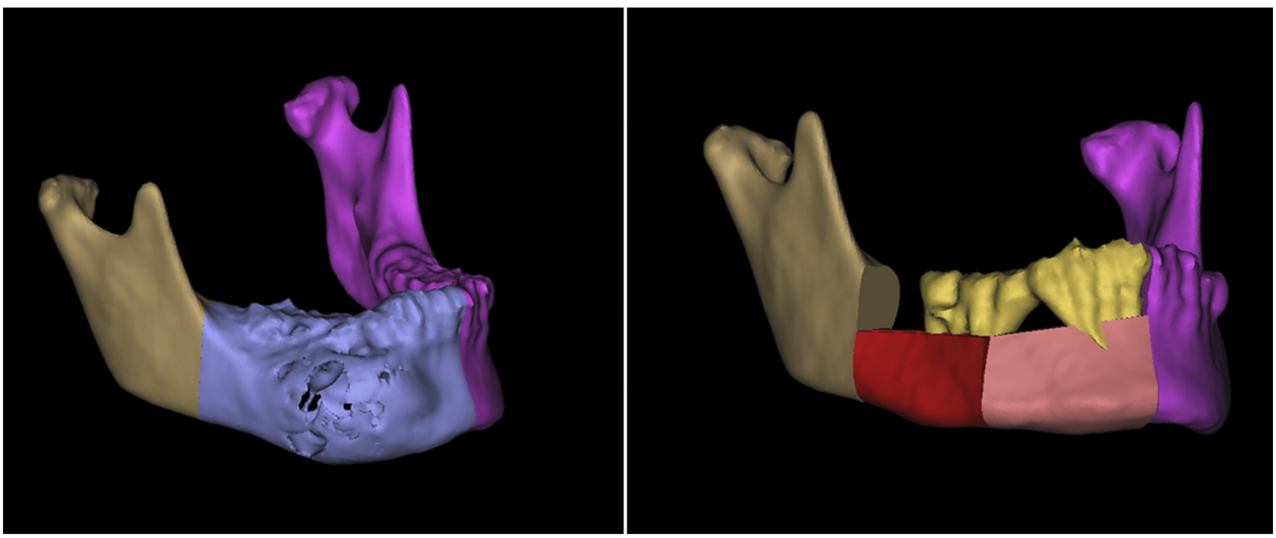

FIGURE 2. Simulation of virtual osteotomy and mandibular reconstruction with the vascularized iliac crest flap on ProPlan CMF software (Materialise, Leuven, Belgium).

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FIGURE 3. Fabrication of the reconstructed mandibular stereomodel. The reconstruction plate is prebent and fixed on the reconstructed mandibular model using 2 titanium screws.

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match the actual maxillofacial skeleton and navigation images on the working station. The precondition for using the navigation process was that the mandible must 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, whereas the other was to choose 3 distinctive anatomic landmarks on the surface of the remaining mandible and register these points with the virtual image. We used the former method in our study. 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. 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 then used to accomplish the osteotomy. After the osteotomy, the occlusion was fixed by the arch bar and the osteotomy site was confirmed again using surgical navigation. The reconstruction plate was fixed on the remaining mandible according to the 6 marked points indicating the positions of the titanium screws (Fig 5). The iliac crest flap was shaped according to the computer-aided design (CAD).

Before the surgical procedure, the bilateral iliac crests were artificially superimposed on the mirror mandible to choose the optimal donor region in shape and geometry. The virtual osteotomy of the iliac crest was determined by the contour of the mirror mandible. Then, the stereomodel of the optimal donor region in the iliac crest was made to guide the

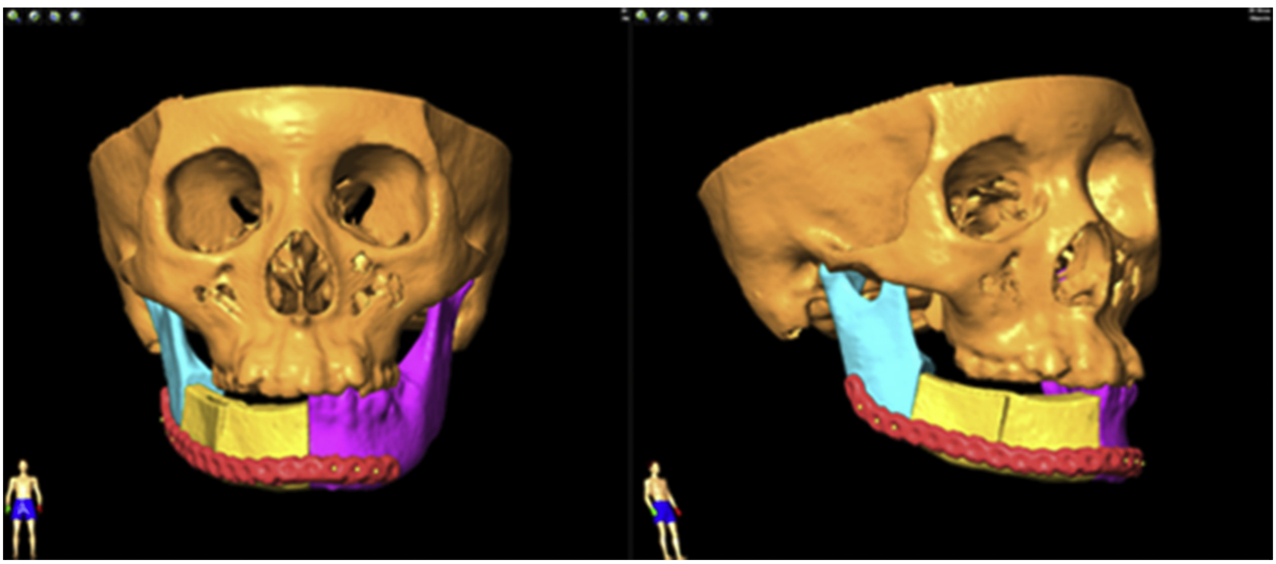

FIGURE 4. Registration of the reconstructed mandible with the reconstruction plate in the surgical navigation system. The 6 points on the 2 sides of the reconstruction plate are marked.

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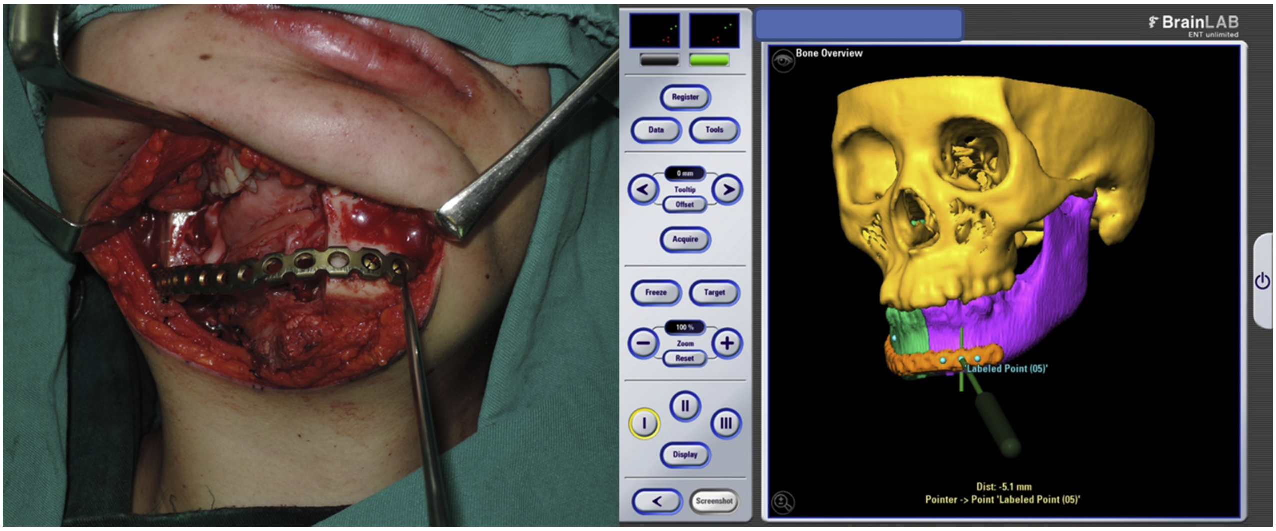

FIGURE 5. Fixation of the reconstruction plate on the remaining mandible according to the 6 marked points indicating the positions of the titanium screws.

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osteotomy of the iliac crest (Fig 4). The vascularized iliac crest flap used in our patient was an iliac muscle flap without skin. In harvesting the vascularized iliac crest flap, the lateral femoral cutaneous nerve should be identified and protected. According to the position of the nerve, the deep circumflex iliac vessels could be identified easily; harvesting of the iliac crest was then performed using the cutting template according to preoperative virtual planning (Fig 6). During surgery, the 3D position of the iliac crest was guided and checked by the navigation system until all segments coincided with the ideal preplanned positions (Fig 7). After the inset of the iliac crest, the facial artery and external jugular vein were used for anastomosis. Figure 8 shows a flow diagram for mandibular reconstruction with the vascularized iliac crest flap using virtual surgical planning and surgical navigation.

Results

The operative time spent on our patient was 370 minutes. The vascularized iliac crest survived successfully without any complications. With this patient's approval, the cost of the entire treatment was increased by ¥4,800 (around US $725) and the time we spent preparing this operation was 2 days longer than that for the traditional surgical procedure because of the virtual plan and surgical navigation. The 3D model of the mandible and iliac crest cost ¥2,000 (around US $300), and the navigation system used during the operation cost ¥2,800 (around US $425). The patient is now receiving orthodontic treatment because of crowded dentition.

A non–contrast-enhanced CT scan was obtained 1 month after the operation to evaluate the

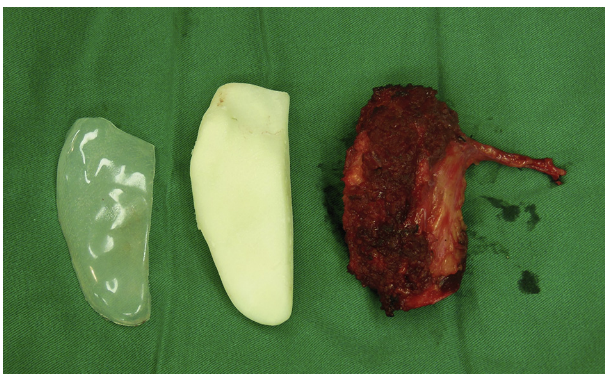

FIGURE 6. Harvesting of the vascularized iliac crest flap by the cutting template.

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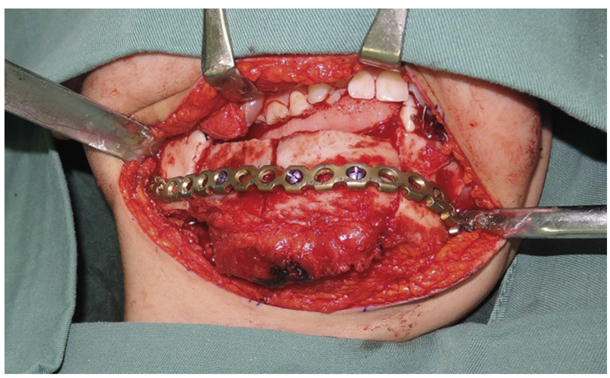

FIGURE 7. Operative view after fixation of the reconstruction plate and inset of the iliac crest.

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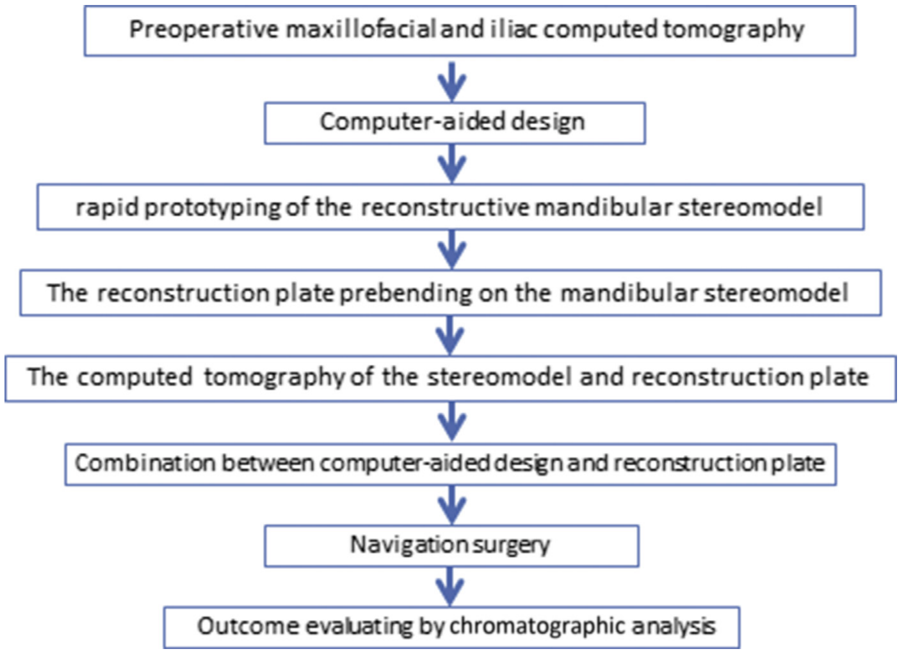

FIGURE 8. Flow diagram for mandibular reconstruction with the vascularized iliac crest flap using virtual surgical planning and surgical navigation.

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outcome of mandibular reconstruction. Chromatography (Geomagic, Morrisville, NC) was used to evaluate the difference between the postoperative configuration of the mandible and the planned configuration.

Using our method, we precisely recovered the original configuration of the mandible (Fig 9). The bilateral condyles were located in the temporomandibular joint fossae. Compared with the preoperative position, the average shift on the left side of the mandible with teeth was 0.023 ± 0.764 mm. The largest shift on this side was 4.512 mm, whereas the largest shift of the osteotomy line on this side was 3.589 mm (Fig 10). The corresponding values on the right side without teeth were 0.318 ± 2.306 mm, 3.460 mm, and 2.671 mm, respectively (Fig 11). The accuracy of the osteotomy site

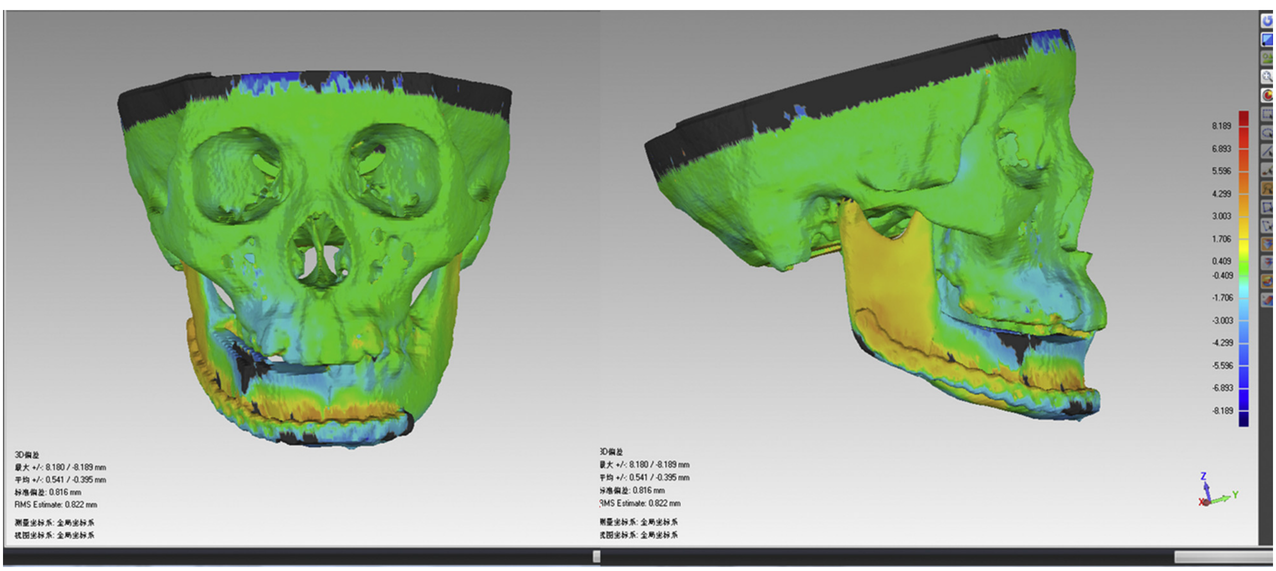

FIGURE 9. Chromatographic analysis of the mandible before and after the operation.

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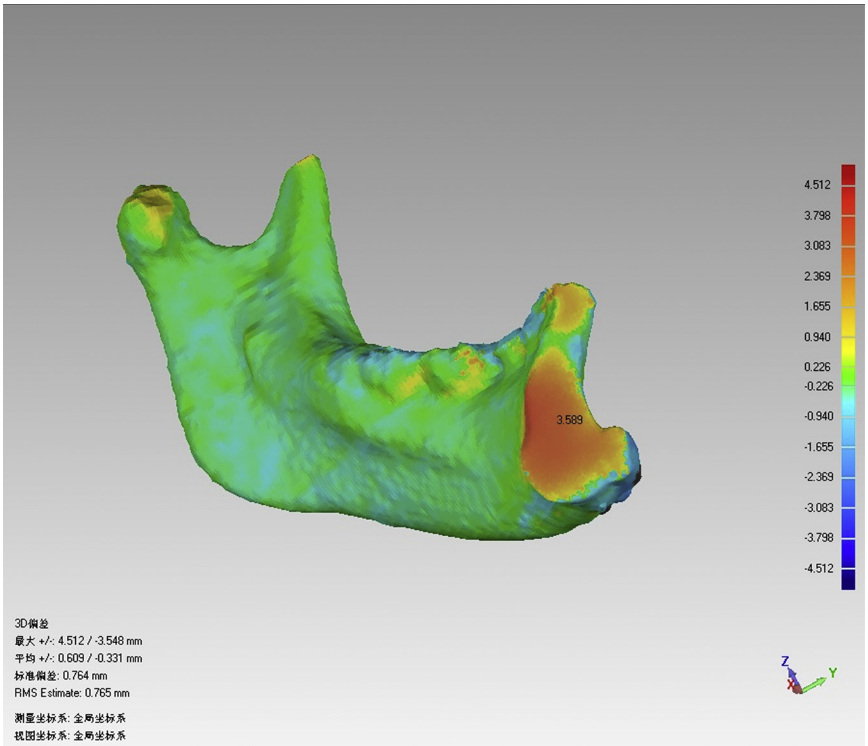

FIGURE 10. Chromatographic analysis of the unilateral mandible with teeth before and after the operation.

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between the 2 iliac crest segments was evaluated. Compared with the preoperative design, the shift of the osteotomy site was 0.29 ± 0.34 mm (Fig 12). Chromatography showed a slight change in the facial contour at 4 weeks after surgery, which was not attributed to postoperative swelling (Fig 13).

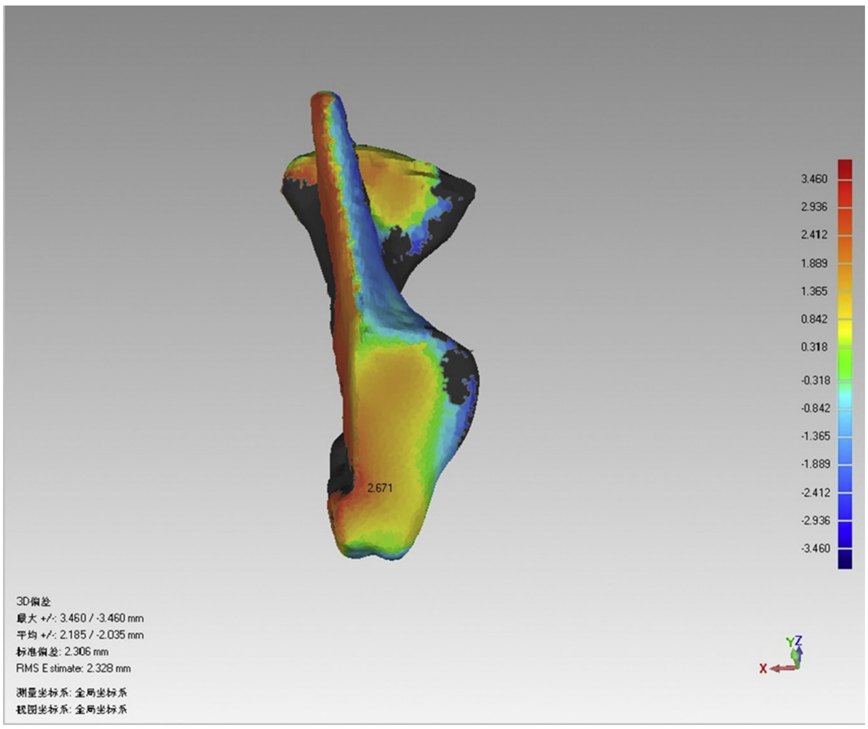

FIGURE 11. Chromatographic analysis of the unilateral mandible without teeth before and after the operation.

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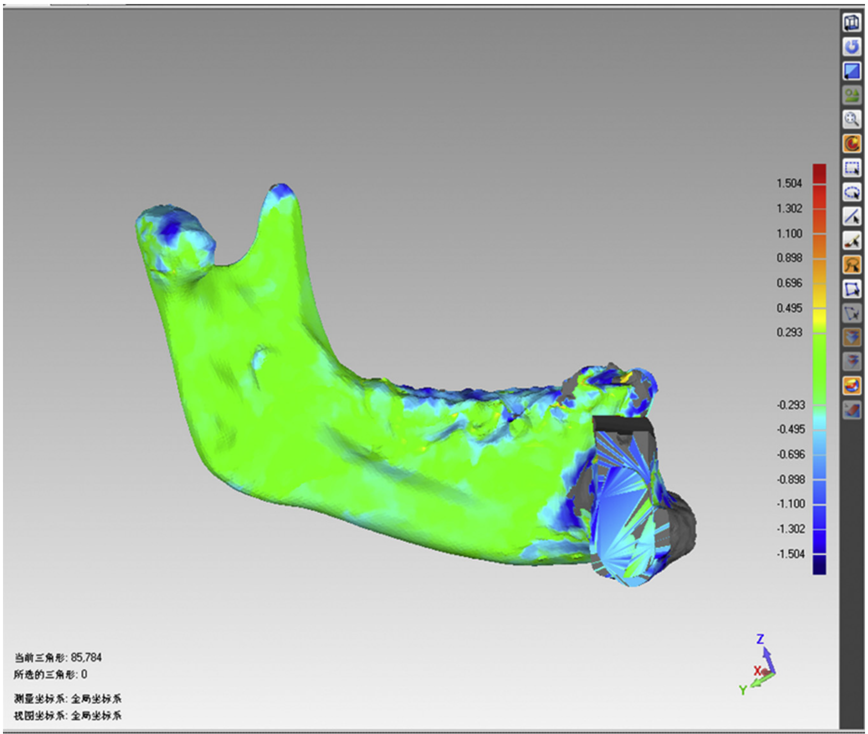

FIGURE 12. Chromatographic analysis of the osteotomy site between the 2 iliac crest segments before and after the operation.

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Discussion

Several studies have focused on computer-assisted mandibular reconstruction with the vascularized iliac crest flap,[6,15,16] wherein computer-assisted design is used for fabricating a mandibular stereomodel as a guide to prebend the reconstruction plate before

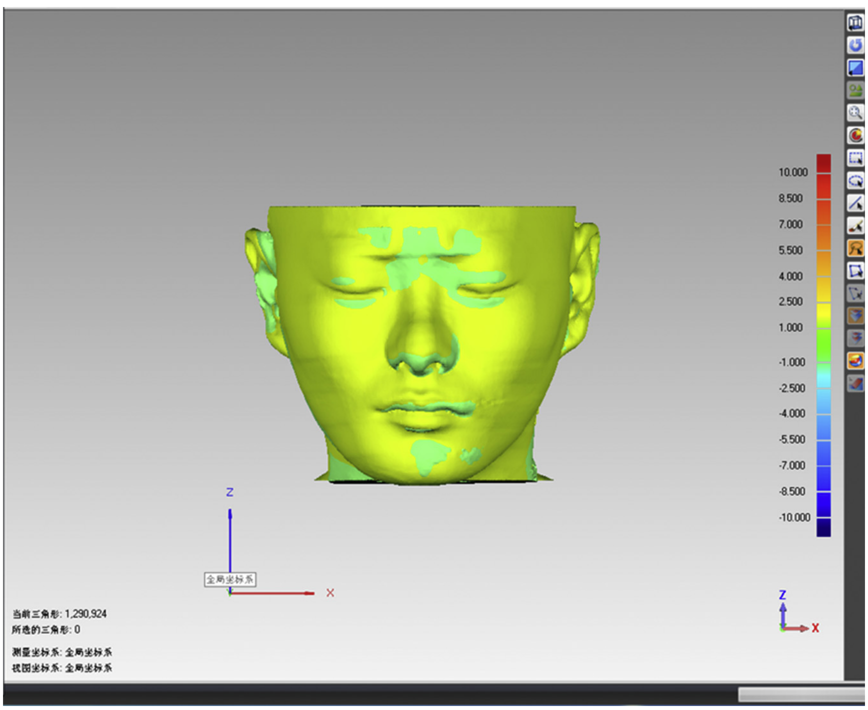

FIGURE 13. Chromatographic analysis of the facial contour before and after the operation.

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real-time surgery. Research on the accuracy of this method showed that it can restore the original configuration of the mandible regarding position and shape with high accuracy.[6] However, the accuracy of this method depends on the gap size between the prebent reconstruction plate and the actual mandible. During mandibulectomy in particular, the mobility of the mandible on both sides can increase the difficulty of reconstruction plate fixation.

The indications for use of intraoperative navigation are as follows: *1)* The occlusion is stable. Before and after the osteotomy, the occlusion should be reproducible. *2)* The tumor is benign. The time and cost are greater than those for traditional surgery, and most patients with malignant tumors are anxious and tense.

In the method used in this study, we subjected the fabricated mandibular stereomodel and reconstruction plate to CT to input the image of the reconstruction plate in the navigation system. During surgery, surgical navigation was used to determine the position of the reconstruction plate, which further confirmed the position of the mandible. Mandibular reconstruction is a challenging task in the field of head and neck reconstructive surgery because of the mobility of the mandible. After mandibulectomy, it may be impossible to fix 1 side of the mandible with an arch bar splint, thus increasing the difficulty of reconstruction. Marchetti et al[17] reported on 4 different preplating techniques to maintain the position of the remaining mandible before mandibulectomy. However, these methods were found to increase the surgical duration and patient trauma. In our method, we fabricated a dental splint to fix 1 side of the mandible to the skull to control mobility. The 3 points indicating the positions of the titanium screws on the fixed side of the mandible were determined by surgical navigation. Then, these 3 marked points guided the correct positioning of the reconstruction plate under surgical navigation, whereas the other 3 marked points verified the same. Once the position of the reconstruction plate was determined, the position of the mobile mandible was approximately determined from the flexibility between the mobile mandible and the reconstruction plate and was finally verified by the osteotomy line placed on the mobile mandible under surgical navigation. Chromatographic analysis showed that the side of the mandible with teeth was closer to the original compared with the contralateral side.

The position of the side of the mandible with teeth was determined as follows: *1)* A dental splint was used to fix this side to the skull. *2)* The reconstruction plate was prebent on the reconstructed mandibular model, and the flexibility between the reconstruction plate and both sides of the mandible aided in determining the position of the mandible. *3)* Surgical navigation guided the position of the mandible and the reconstruction plate. The position of the side of the mandible without teeth was determined by the latter two methods. The results showed that the shift in the reconstructed mandible and plate was less than 5 mm, thus confirming the reliability of this method.

Our method has several advantages: First, it helped in decreasing the duration of mandibular reconstruction and, consequently, the transplant ischemic time. Second, the position of the mandible on both sides could be confirmed by surgical navigation—and not the extra reconstruction plate—thus decreasing the cost of surgery. Third, the testing approach was used to verify the position of the mandible and reconstruction plate, further minimizing the error.

With the help of computer-assisted surgery, different virtual scenarios can be considered for mandibular reconstruction, which provide the clinical benefits of predictable anatomic dimensions, reconstruction limitations, and possible complications.[18,19] Currently, CAD–computer-aided manufacturing (CAM) technologies are applied for mandibular reconstruction with the vascularized iliac crest flap, wherein the reconstruction plate is prebent on a 3D model, thus decreasing the ischemic time. There is a significant relationship between the ischemic time and the flap survival rate,[20] and our method minimizes the ischemic time interval between flap delivery and revascularization.

CAD-CAM technologies also offer cutting guides for the mandible and iliac crest, which can improve the accuracy of 3D contouring of the iliac crest. However, these technologies are associated with some unresolved problems: First, the exposed surgical field needs to be enlarged to offer enough space for positioning the guide, and this may result in a longer surgical duration and a more invasive procedure. Second, the stability of the iliac cutting guide is influenced by the muscle sleeve, skin paddle, and vessels of the iliac crest flap, which may result in positional variations. If a skin paddle is required for composite reconstruction, it is much more difficult to plan the correct guide position by reference to musculocutaneous perforators. Schepers et al[21] mentioned that the primary error with CAD-CAM was probably caused by incorrect positioning of the guide because of over-riding of the soft tissue underneath the guide in the mental region. Third, there is no verification method to decrease the errors associated with CAD-CAM. Several complex steps are required when CAD-CAM technologies are applied for surgical procedures, thus leading to cumulative errors. Consequently, the final error may be very large, with no way to perform verification during surgery.

The computer navigation technique builds a virtual-reality bridge for bony surgical procedures such as osteotomy, orthognathic surgery, fracture reduction, and bone flap reconstruction.[22] Previously, computer-aided navigation was not used for mandibular reconstruction because of the mobility of this bone. There are 3 possible solutions to this problem: First, intermaxillary fixation should be maintained during CT and surgery, although it is not feasible for operations using an intraoral approach. Second, the mandible should be placed in centric relation or centric occlusion, either manually or using a dental splint. Although mandibular movements are convenient for surgery, they undermine the accuracy of intraoperative navigation. In this study we selected this solution to overcome the limitation of mobility. Before computer navigation, the mandible was placed in centric relation using an arch bar splint, and its location was verified using 3 point landmarks. Third, the surgeon can use a special sensor frame fixed on 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 procedure is time-consuming, it provides the theoretical advantage of improved accuracy by facilitating direct monitoring of the position of the mandible, rather than determining the position in relation to other fixed cranial structures.[23]

Numerous studies have focused on the improvement of computer-aided navigation for mandibular reconstruction, with some success. For example, in 2008, Casap et al compared 2 navigation systems for mandibular reconstruction.[24] The first system was the Image Guided Implantology system (Tom Wilson, Dallas, TX), which uses a tooth-mounted sensor frame directly attached to the mandible and is specifically designed for implant placement. The navigation error for this system was calculated to be less than 0.5 mm. The second system was the LandmarkX system (Medtronic, Minneapolis, MN), which uses a headset frame and requires the mandible to remain immobilized during surgery. The accuracy of this system was 3 to 4 mm. However, the previous studies have focused on the position of a point or osteotomy line in a model or cadaver.[25]

Mandibular defects resulting from tumor resection and trauma are commonly encountered by oral and maxillofacial surgeons. Several options for mandibular reconstruction are available, among which the vascularized iliac crest flap has exhibited many advantages for patients. Achieving functional and esthetic goals solely on the basis of experience is difficult for surgeons, and computer-assisted techniques such as virtual planning and navigation surgery are a potential solution to this problem. In this study we described a new method for mandibular reconstruction with the vascularized iliac crest flap and an individual reconstruction plate using computer-assisted techniques involving surgical navigation, which can improve the clinical outcomes of this procedure.

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