Three-Dimensional Accuracy of Virtual Planning and Surgical Navigation for Mandibular Reconstruction With Free Fibula Flap

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Purpose: Although free fibula flaps are widely used for mandibular reconstruction, their 3-dimensional position is difficult to control during conventional surgery. We aimed to improve this process by using computer-aided design (CAD) and surgical navigation.

Patients and Methods: We retrospectively reviewed 29 benign tumor patients who underwent primary unilateral mandibular reconstruction with free fibula flap. They were divided into 3 groups: group A, comprising 10 patients, underwent reconstruction based on the surgeon's experience; group B, comprising 7 patients, underwent reconstruction based on CAD; and group C, comprising 12 patients, underwent reconstruction based on CAD and surgical navigation. Condyle and gonion positions and mandibular angles were measured. Operative times were recorded.

Results: Among the 17 patients who underwent condylar resection, the average condyle shift was greater in group A than in groups B and C ($P < .05$). The average gonion shift was greater in groups A and B than in group C ($P < .05$). The difference between the reconstructed and contralateral mandibular angles was greater in group A than in groups B and C ($P < .05$). The mean operative time did not differ among the 3 groups.

Conclusions: CAD can guide mandibular angle remodeling and condyle placement. CAD and surgical navigation increase reconstruction accuracy without prolonging operative time.

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Mandibular reconstruction is a challenging task in head and neck reconstructive surgery, which aims to achieve the best possible functional and esthetic outcomes. In 1989 Hidalgo[1] demonstrated the utility of free vascularized fibula flaps for mandibular reconstruction. Since then, the fibula flap has become a highly reliable and popular flap for mandibular reconstruction.[2] This flap has many advantages, including a long pedicle length, a wide vessel diameter, and the ability to incorporate skin, muscle, and bone components, which are required for mandibular reconstruction.[3] The mobility of the mandible increases the difficulty in achieving fibula flap inset and influences the accuracy of mandibular reconstruction.

Computer-assisted surgery is becoming increasingly popular in the field of oral and maxillofacial surgery.

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In the past, the 3-dimensional (3D) position of the free fibula flap was very difficult to control because the operation was based solely on the surgeon's experience. Thus, such operations occasionally resulted in dissatisfying occlusion and appearance. However, with the application of virtual technology, mandibular reconstructions are becoming increasingly accurate.[4-6] The first such technology used for mandibular reconstruction was computer-aided design (CAD). CAD can be used to mark osteotomy lines and calculate the lengths and angles of bone segments by simulating the operative process. Soon afterward, CAD–computer-aided manufacturing (CAM) and rapid prototyping, which were introduced in the past decade, improved the precision of mandibular reconstruction.[7] At the same time, it became possible to import virtual data to a navigation system, which was used to provide guidance for the accurate and safe placement of hardware or bone grafts, movement of bone segments, tumor resection, and osteotomy design. Finally, newly designed, mobile, intraoperative computed tomography (CT) scanners became available and could be used to confirm the accuracy of reconstruction before patients left the operating room.[8] Many appliances and studies about navigation surgery have concentrated on the midface region.[9,10] Navigation surgery has rarely been used for mandibular reconstruction because of the mobility of the mandible. The purpose of this study is to improve the process of mandibular reconstruction by using CAD and surgical navigation.

Patients and Methods

PATIENTS

We retrospectively reviewed the cases of 29 patients who had undergone mandibulectomy for the removal of benign tumors and mandibular reconstruction with free fibula flaps at Peking University School and Hospital of Stomatology between June 2013 and June 2014. The inclusion criteria were *1)* stable occlusal status, *2)* unilateral mandibular lesion including the mandibular angle, and *3)* division of the free fibula into 2 or more segments fixed by miniplates.

The patients were divided into the following 3 groups according to the type of surgery: group A (10 patients), reconstruction performed based on the surgeon's clinical experience; group B (7 patients), reconstruction performed using CAD; and group C (12 patients), reconstruction performed using both CAD and computer-assisted navigation. In all groups, miniplates were used to fix the fibula bone with the residual mandible. The condyle was resected in 4, 5, and 8 patients in groups A, B, and C, respectively. All tumor resections and mandibular reconstructions were performed by the same chief surgeon (X.P.).

TECHNIQUES

Computer-Aided Design

The process of CAD began with the acquisition of high-resolution CT scans of the maxillofacial skeleton and lower extremities. The imaging and planning platform used in this study was Surgicase CMF (Materialise, Leuven, Belgium). This software allowed the creation of 3D virtual models of the maxillofacial skeleton and fibula, as well as the simulation of mandibular osteotomies. Then, we superimposed the 3D fibular image onto the mandibular defect in its desired orientation. If the contour of the mandible was destroyed by the tumor, mirroring tools were used.[11] The length of every fibular segment and the angle between 2 fibular segments were measured and provided to the surgeon to facilitate intraoperative positioning and placement. The position of the osteotomy line and relevant parameters regarding shaping the fibula flap also were provided to the surgeon.

CAD and Navigation Surgery

Intraoperative navigation is comparable to global positioning systems commonly used in automobiles and is composed of 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 a vehicle; and a CT scan data set, which is analogous to a road map. The navigation system used in this study was iPlan 3.0 (Brainlab, Feldkirchen, Germany). Mandibular reconstruction with CAD and navigation surgery included a planning phase and a surgical phase. CAD was completed during the planning phase. CT images of the CAD in stereolithography (STL) format were imported to iPlan 3.0 to register with the original CT imaging data. The navigation data were exported into a universal serial bus (USB) drive, which was then connected with the CT scan data set during the operation. The intraoperative navigation consisted of 3 primary components: CT scan data set, surgical probe, and localizer.

In the surgical phase, the first step was to secure fixed markers to the patient's head by way of screws inserted through small incisions in the scalp. The operator registered a series of points on the face with the CT data set to match the actual maxillofacial skeleton and the navigation images. The precondition for using the navigation process was that the mandible could be kept closed against the maxilla in centric occlusion and could be maintained throughout the navigation process. This closure could be accomplished by 2 methods. One method was to fix the mandible in centric occlusion with arch bar splint fixation, if possible. The other was to choose 3 distinctive anatomic landmarks on the surface of the remaining mandible and register these points with the virtual image. Through these 2 methods, the mandible was located in the planned position. Intraoperative navigation was used to implement the virtual plan for patients undergoing mandibulectomy and mandibular reconstruction. The available sagittal, coronal, axial, and 3D reconstruction images displayed by the navigation system were used intraoperatively to accurately determine the osteotomy sites as well as the correct osteotomy trajectory. Under the guidance of a surgical probe, the osteotomy line was marked and the virtual mandibulectomy surgical procedure was transferred into reality. The fibula was shaped according to the CAD and recorrected by the surgical navigation.

Ethical approval was obtained for our study (ethical approval document number PKUSSIRB-201522048). This study features human participants, and we confirm that we have read the Helsinki Declaration and have followed the guidelines in this investigation.

DATA ANALYSIS

The follow-up period was 6 months after the surgical procedure. Postoperative occlusion and appearance satisfaction were evaluated in the sixth month after the surgical procedure.

A postoperative maxillofacial CT scan of a 1-mm slice was obtained for each patient 6 months after the surgical procedure. The preoperative and postoperative CT data were transferred to Surgicase CMF. The ideal and actual positions of the gonion of the reconstructed mandible were compared using iPlan 3.0 (Fig 1). In groups B and C, the ideal gonion position was determined using CAD. In group A, the ideal gonion position was confirmed by referring to the preoperative gonion position or by using mirroring tools, when the contour of the mandibular angle had been destroyed by the tumor. The same methods also were used to evaluate the position of the reconstructed condyle (Fig 2). The preoperative 3D image of the mandible including the ideal gonion and condyle was imported and matched with the postoperative 3D image. The 2 images were overlaid in the same coordinate system. The 3D coordinates of the ideal and reconstructed gonion and condyle were measured, and the gonion shift and condyle shift (defined as the distance between the ideal and reconstructed gonion and condyle, respectively) were then calculated. The preoperative and postoperative CT scans of the 29 patients were positioned in the same coordinate system. The interpupillary line was defined as the x-axis, the line between the anterior and posterior nasal spine was the y-axis, and the z-axis was perpendicular to the x-axis and y-axis. The gonion shift and condyle shift in every axis were then measured.

The angles of the ideal and reconstructed mandibles also were measured. The normal mandibular angle was measured using 3 points (A, B, and C). Point A was the point of intersection between the osteotomy line of the mandibular ramus and the posterior margin of the mandibular ramus. If the condyle was resected, point A was the upper and posterior margin of the condyle. Point B was the ideal gonion. Point C was the point of intersection between the osteotomy line of the mandibular body and the inferior margin of the mandibular body. The difference between the ideal and reconstructed mandibular angles (angle variation) was calculated.

A single, non-blinded biomedical engineer performed all the linear measurements. The aforementioned measurements were used to evaluate the accuracy of mandibular reconstructions using different techniques. In addition, the operative time was recorded in each group. The operative times in group C were used to plot a learning curve for reconstructions assisted by CAD and surgical navigation. The differences in condyle shift, gonion shift, angle variation, and operative time were compared among the 3 groups by using 1-way analysis of variance. All statistical analyses were performed with SPSS software (version 13.0; SPSS, Chicago, IL).

Results

This retrospective case series involved 29 consecutive patients (16 male and 13 female patients), with an average age of 33 years (range, 8-58 years), who underwent surgical resection of benign tumors (Table 1). In most patients, the primary tumor was an ameloblastoma (n = 21, 72.4%). All fibula flaps in all 3 groups survived postoperatively.

The condyle was retained in 12 patients; all retained condyles on the affected side were located in the temporomandibular joint (TMJ) fossa. Among patients who underwent condylar resection, the average condyle shift (distance between reconstructed and ideal condyle positions) was significantly greater in group A (18.4 ± 2.9 mm) than in group B (10.3 ± 3.9 mm) and group C (9.3 ± 2.6 mm) ($P < .05$). There was no significant difference in condyle shift between groups B and C. Among the 17 patients, the average condyle shift along the z-axis was significantly lower in groups B and C than in group A ($P < .05$). The average gonion shift (distance between reconstructed and ideal gonion positions) was greater in group A (12.8 ± 3.8 mm) and group B (12.5 ± 3.8 mm) than in group C (7.3 ± 2.5 mm) ($P < .05$). There was no significant difference in gonion shift between groups A and B. The gonion shift along the z-axis was significantly higher than that along the x-axis and y-axis in groups A and B ($P < .05$). Angle variation (between the

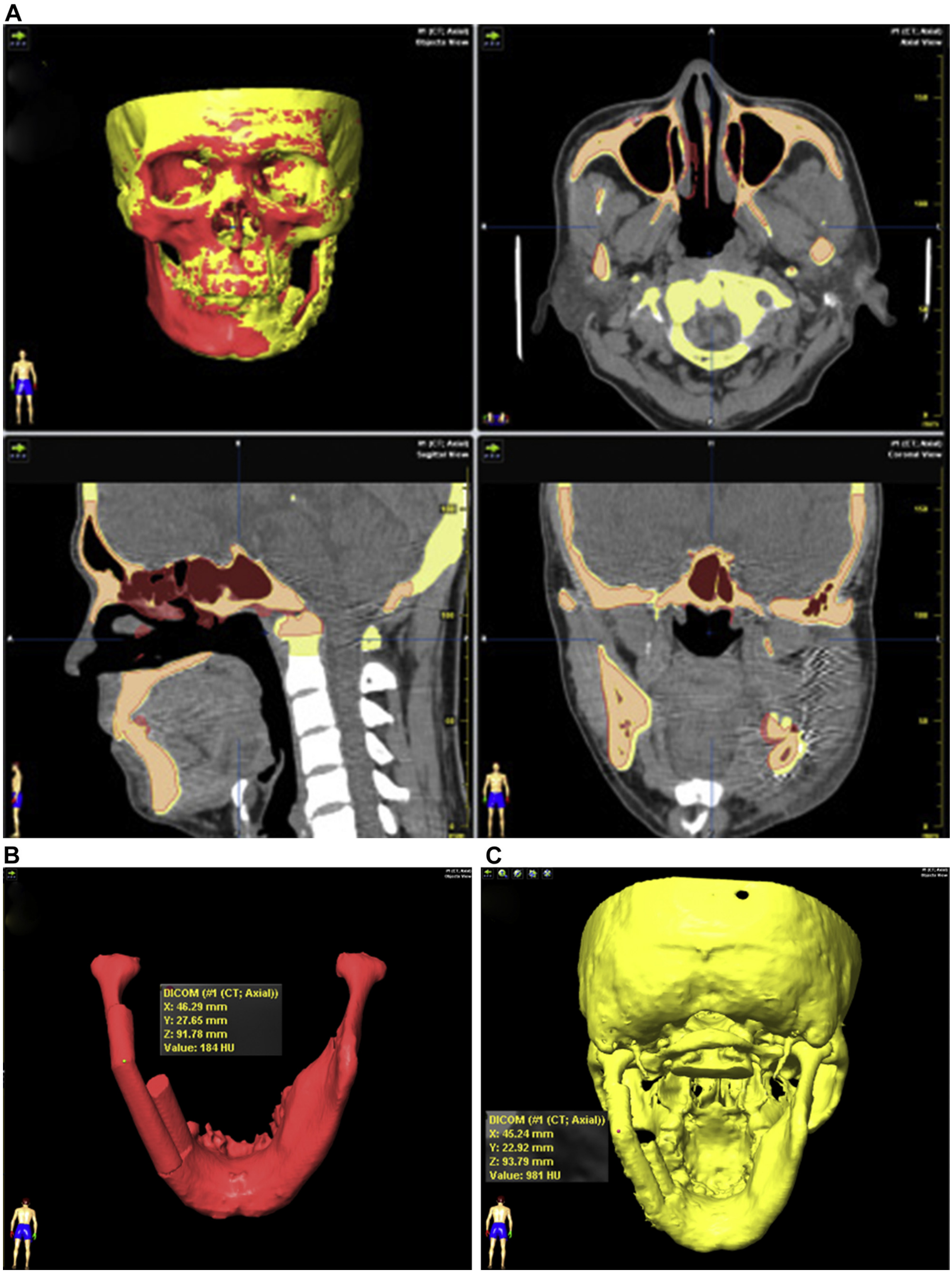

FIGURE 1. *A*, Image registration between postoperative skull and ideal mandible. *B*, Marking of ideal mandibular angle. *C*, Marking of actual mandibular angle on postoperative mandible. CT, computed tomography; DICOM, digital imaging and communications in medicine; HU, Hounsfield units.

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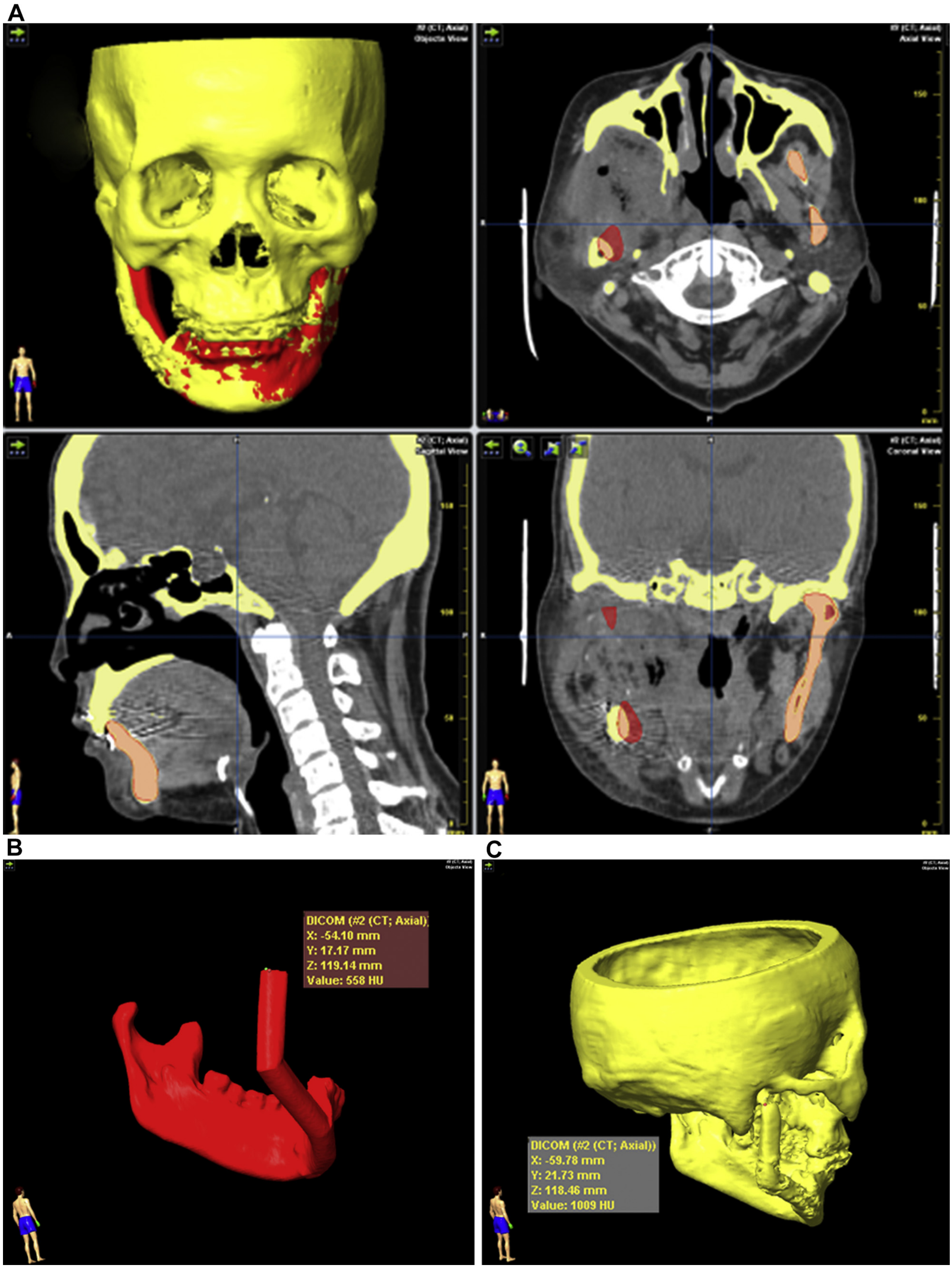

FIGURE 2. *A*, Image registration between postoperative skull and ideal mandible. *B*, Marking of ideal condyle. *C*, Marking of actual condyle on postoperative mandible. CT, computed tomography; DICOM, digital imaging and communications in medicine; HU, Hounsfield units.

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Table 1. PATIENT DEMOGRAPHIC DATA

Patient	Age, yr	Gender	Site	Diagnosis
Group A				
Case 1	37	F	Body, ramus, condyle	Ameloblastoma
Case 2	61	M	Body, ramus, condyle	Keratocyst
Case 3	19	M	Body, ramus, condyle	Ameloblastoma
Case 4	35	M	Body, ramus	Ameloblastoma
Case 5	55	M	Body, ramus	Keratocyst
Case 6	41	F	Body, ramus	Fibrous dysplasia
Case 7	34	F	Body, ramus	Ameloblastoma
Case 8	34	M	Body, ramus	Dentinogenic ghost cell tumor
Case 9	26	F	Body, ramus	Ameloblastoma
Case 10	31	F	Body, ramus, condyle	Ameloblastoma
Group B				
Case 1	16	F	Body, ramus, condyle	Ameloblastoma
Case 2	20	M	Body, ramus, condyle	Ameloblastoma
Case 3	53	F	Body, ramus, condyle	Ossifying fibroma
Case 4	9	M	Body, ramus, condyle	Fibrous dysplasia
Case 5	22	F	Body, ramus, condyle	Ameloblastoma
Case 6	30	F	Body, ramus	Ameloblastoma
Case 7	47	F	Body, ramus	Ameloblastoma
Group C				
Case 1	48	F	Body, ramus, condyle	Ameloblastoma
Case 2	20	M	Body, ramus, condyle	Ameloblastoma
Case 3	13	M	Body, ramus, condyle	Ameloblastoma
Case 4	58	F	Body, ramus, condyle	Ameloblastoma
Case 5	51	M	Body, ramus, condyle	Keratocyst
Case 6	28	M	Body, ramus, condyle	Ameloblastoma
Case 7	8	M	Body, ramus, condyle	Ameloblastoma
Case 8	27	F	Body, ramus, condyle	Ameloblastoma
Case 9	18	M	Body, ramus, condyle	Ameloblastoma
Case 10	53	M	Body, ramus	Ameloblastoma
Case 11	50	M	Body, ramus	Ameloblastoma
Case 12	27	M	Body, ramus	Dentinogenic ghost cell tumor

Abbreviations: F, female; M, male.

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reconstructed and contralateral mandibles) was significantly greater in group A (8.7° ± 4.3°) than in group B (3.1° ± 2.0°) and group C (2.6° ± 1.4°) ($P < .05$). The mean operative time did not significantly differ among groups A (402 ± 42 minutes), B (392 ± 55 minutes), and C (365 ± 32 minutes) (Fig 3, Tables 2 and 3).

In this study all 29 free fibula flaps survived without any complications. The postoperative occlusion of the 29 patients in the sixth month after the surgical procedure was stable and the same as the preoperative situation. All 29 patients were satisfied with the facial appearance. There was no significant difference among the 3 groups in clinical outcome.

Discussion

Miniplates and reconstruction plates are usually used to fix free fibula flaps, the gold standard in the reconstruction of large segmental mandibular defects. Miniplates and reconstruction plates have different characteristics that provide different advantages and disadvantages regarding neomandibular fixation. Miniplate fixation, which was introduced by Hidalgo,[1] is thought to be associated with greater malleability, a lower facial profile, a decreased operative time, and a decreased risk of disruption of the vascular pedicle.[12] Kennady et al[13] suggested that reconstruction plates were associated with stress shielding and disuse osteoporosis. Robey et al[14] compared patients who had undergone fibular reconstruction of mandibular defects with miniplates with patients who had undergone this repair using reconstruction plates. No statistically significant difference was identified between the miniplate group and reconstruction plate group regarding overall cumulative complication rates, flap failure, plate extrusion, malunion or nonunion, and plate fracture. Furthermore, miniplate fixation can be performed at the donor site before harvesting the vascular pedicle.[14] In this study, miniplates were

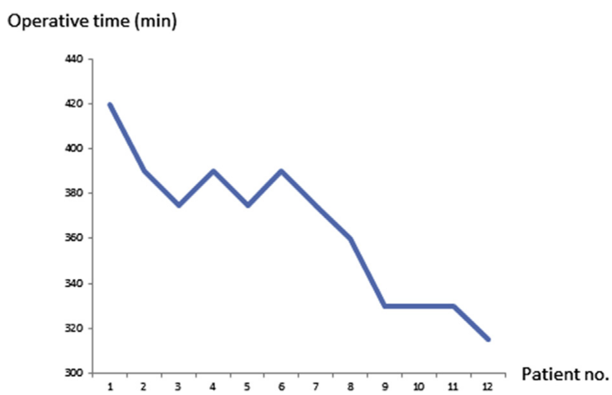

FIGURE 3. Learning curve showing operative time for surgical procedures assisted by computer-aided design and surgical navigation in group C.

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Table 2. MEASUREMENT DATA FOR RECONSTRUCTED MANDIBLES AND OPERATIVE TIME

Patient	Condyle Shift, mm	Gonion Shift, mm	Angle Difference, °	Operation Time, min
Group A				
Case 1	17.00	16.49	14.7	330
Case 2	21.10	18.67	6.4	420
Case 3	18.07	10.77	5.7	420
Case 4	13.50	11.46	6.6	375
Case 5	—	12.69	10.5	375
Case 6	—	12.92	5.6	390
Case 7	—	8.56	8.3	375
Case 8	—	15.35	7.7	480
Case 9	—	5.9	4.1	435
Case 10	—	15.70	17.5	420
Group B				
Case 1	5.20	12.28	1.5	360
Case 2	9.10	8.42	0.5	390
Case 3	16.10	13.73	5.0	360
Case 4	10.50	16.24	4.6	345
Case 5	10.40	14.76	4.7	510
Case 6	—	6.18	4.7	390
Case 7	—	15.63	1.0	390
Group C				
Case 1	4.1	6.57	4.50	420
Case 2	11.4	12.82	1.80	390
Case 3	10.3	8.01	2.70	375
Case 4	11.3	7.95	2.90	390
Case 5	9.8	6.80	0.40	375
Case 6	10.6	9.07	0.40	390
Case 7	10.2	5.30	3.49	375
Case 8	6.5	6.70	2.30	360
Case 9	—	4.95	1.50	330
Case 10	—	5.73	4.70	330
Case 11	—	3.64	3.50	330
Case 12	—	10.4	3.30	315

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used to fix the mandible and fibula because the position of the gonion or condyle reconstructed using a fibula flap can be easily adjusted, but it is not easy to reach the accurate position at the same time.

This retrospective case series compared postoperative CT data with preoperative surgical or CAD data. We selected specific linear and angular 3D CT measurements as indicators of mandibular reconstruction (planned vs actual condyle and gonion positions and ideal vs actual mandibular angle) because these measurements have been found to be accurate, irrespective of scanner parameters or rendering technique.[15]

The position of the reconstructed condyle is crucial for postoperative mandibular function. In patients who underwent condylar resection, the transferred fibula flap was fixed unilaterally with the residual mandible, which reduced the stability of the fibula. The masticatory muscles with attachment loss, zygomatic arch, and skull base formed the path of fibula insertion. A deviated reconstructed condyle can lead to an asymmetric facial profile, limited mouth opening, and instability of the transferred fibula. In our study, all the preserved condyles on the affected side (12 patients) were located in the TMJ fossa. Among the other 17 patients, the average condyle shift was significantly lower in groups B and C than in group A ($P < .05$). The soft and hard tissues near the TMJ provide a reference for the reconstruction of the condyle and mandibular ramus.[16] The preoperative and postoperative CT scans of these 17 patients were positioned in the same coordinate system. The interpupillary line was defined as the x-axis, the line between the anterior and posterior nasal spine was the y-axis, and the z-axis was perpendicular to the x-axis and y-axis. In these 17 patients, the average condyle shift along the z-axis was significantly lower in groups B and C than in group A ($P < .05$) (Table 4). We found that the most common reason for condylar deviation was shortness of the reconstructed mandibular ramus. It is very difficult to confirm whether the top of the transferred fibula is inserted precisely into the glenoid fossa because fossa exposure is not adequate on the table. Using CAD and surgical navigation, we can know the length of the reconstructed mandibular ramus before the surgical procedure, and the top of the fibula can be verified during the operation.

The gonion position is also important in mandibular reconstruction. In this study the gonion shift was significantly lower in group C (reconstruction based on CAD and surgical navigation) than in groups A and B. However, the gonion shift did not significantly differ between group A (reconstruction based on surgeon's experience) and group B (reconstruction based on CAD). The gonion shift along the z-axis was significantly higher than that along the x-axis and y-axis in groups A and B ($P < .05$) (Table 4). The gonion shift in the z-axis was positive, which indicated that the most common reason for the gonion shift was that the reconstructed gonion was lower than the preoperative position in groups A and B. This result may be attributable to 2 possible reasons: First, although preoperative CAD provides some parameters such as defect length and angle between 2 bone segments, accurate 3D contouring of the fibula based on these parameters is very difficult, especially when there are more than 2 segments in the fibula flap. Second, the location of the gonion in the turning point of the mandible without any landmarks increases the difficulty in gonion positioning because of the lack of intraoperative verification, even though the preoperative CAD position may be used for reference.

Table 3. THREE-DIMENSIONAL POSITION OF FIBULA AND OPERATIVE TIME IN GROUPS A, B, AND C

	Condyle Shift	Gonion Shift	Angle Variation	Operation Time
Group A	17.4 ± 3.1 mm	12.8 ± 3.8 mm	8.7° ± 4.3°	402 ± 42 min
Group B	10.3 ± 3.9 mm	12.5 ± 3.8 mm	3.1° ± 2.0°	392 ± 55 min
Group C	9.3 ± 2.6 mm	7.3 ± 2.5 mm	2.6° ± 1.4°	365 ± 32 min
P value				
Group A vs group B	.004*	.816	.001*	.636
Group A vs group C	.001*	< .001*	< .001*	.048
Group B vs group C	.590	.003*	.707	.183

* $P < .01$.

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The angle of the reconstructed mandible is important for the facial profile. In this study, angle variation (difference between reconstructed and contralateral mandibular angles) was significantly higher in group A (8.7° ± 4.3°) than in group B (3.1° ± 2.0°) and group C (2.6° ± 1.4°). The aforementioned results show that CAD and surgical navigation helped improve the accuracy of mandibular reconstruction.

Table 4. THREE-DIMENSIONAL DATA (X-, Y-, AND Z-AXIS) FOR CONDYLE AND GONION

	Condyle, mm				Gonion, mm			
Patient	Shift	x-Axis	y-Axis	z-Axis	Shift	x-Axis	y-Axis	z-Axis
Group A								
Case 1	17.00	−9.81	−4.09	13.24	16.49	−5.27	−3.45	15.25
Case 2	21.10	15.98	−1.10	13.74	18.67	−3.38	−0.81	18.35
Case 3	18.07	7.20	−4.35	16.00	10.77	8.12	1.88	6.83
Case 4	13.50	10.61	−2.27	8.00	11.46	4.11	−0.34	10.07
Case 5	—				12.69	0.30	−0.77	12.67
Case 6	—				12.92	−7.89	−1.49	10.12
Case 7	—				8.56	−5.48	2.31	6.61
Case 8	—				15.35	−13.63	3.82	5.95
Case 9	—				5.9	−5.80	−1.09	0
Case 10	—				15.70	−12.88	4.93	7.50
Group B								
Case 1	5.20	−0.86	3.93	3.31	12.28	1.71	10.34	6.41
Case 2	9.10	−0.57	0	9.09	8.42	2.16	−3.98	7.71
Case 3	16.10	−0.97	1.58	16.01	13.73	3.50	2.30	13.1
Case 4	10.50	2.37	−1.68	10.06	16.24	5.61	−4.84	14.46
Case 5	10.40	−8.68	0.44	−5.71	14.76	10.18	8.41	6.60
Case 6	—				6.18	1.84	−0.77	5.85
Case 7	—				15.63	3.27	9.42	12.03
Group C								
Case 1	4.1	0.10	3.60	2.01	6.57	0.81	−5.19	3.96
Case 2	11.4	4.70	8.75	5.68	12.82	8.65	−1.59	9.34
Case 3	10.3	−3.13	9.52	2.50	8.01	−4.30	6.65	1.25
Case 4	11.3	9.87	−2.35	−5.00	7.95	−2.35	1.17	−7.50
Case 5	9.8	−8.38	4.18	3.01	6.80	−0.35	−6.82	0.40
Case 6	10.6	−5.23	−8.90	2.22	9.07	2.25	−1.64	8.64
Case 7	10.2	−7.81	3.35	−5.50	5.30	−1.78	−4.97	0
Case 8	6.5	−5.17	3.79	−1.25	6.70	2.41	5.00	5.00
Case 9	—				4.95	−2.80	−3.15	2.60
Case 10	—				5.73	5.20	1.21	2.10
Case 11	—				3.64	0.33	3.62	0.22
Case 12	—				10.4	9.98	1.73	2.50

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CAD allows the manipulation of 3D representations of the mandible and donor site, which can help surgeons plan the resection, measure the defect, and plan the harvest and contouring of the fibula flap.[17] Multiple software programs are available for this planning, which can reduce operative time and enhance the quality of reconstruction.[18] Currently, CAD-CAM technology is widely used for mandibular reconstruction with free fibula flaps.[19,20] This technology offers cutting guides for the mandible and fibula, which can improve the accuracy of 3D contouring of the fibula. However, CAD and CAM technology still has some problems that need to be resolved. The first problem is that the exposed surgical field needs to be enlarged to offer enough space for positioning the guide, and this may result in a longer operative time and a more invasive procedure. The second problem is that the stability of the fibular cutting guide is influenced by the muscle sleeve, skin paddle, and vessels of the fibula flap, which may result in position variation. If a skin paddle is required for composite reconstruction, it is much more difficult to plan the correct guide position by reference to the musculocutaneous perforators. Schepers et al[21] reported that the primary error of CAD and CAM was probably caused by incorrect positioning of the guide, caused by overriding of the soft tissue underneath the guide in the mental region. Compared with CAD and CAM, the advantage of CAD surgery is that there is no need to consider the soft tissue. Finally, the third problem is that no verification method is available to decrease the errors in CAD and CAM. Many complex steps are required when CAD-CAM technology is applied for surgery, which may result in cumulative errors. Thus the final error may be very large, without any way to verify the error during the operation.

Surgical navigation is a powerful tool that enables the accurate execution of a surgical plan.[4] Strong et al[22] evaluated the precision of 3 navigation systems (StealthStation [Medtronic Xomed, Jacksonville, FL]; Voxim [IVS Solutions, Chemnitz, Germany]; and VectorVision [Brainlab]). The difference between the actual surgical probe placement and its virtual location was measured at 9 different landmarks for each system. The StealthStation was found to be the most accurate (1.00 $\pm$ 0.04 mm), followed by VectorVision (1.13 $\pm$ 0.05 mm) and Voxim (1.34 $\pm$ 0.04 mm). The clinical significance of these small differences in maxillofacial reconstruction is still unclear.

The computer navigation technique builds a virtual-reality bridge for bony surgical procedures such as osteotomy, orthognathic surgery, fracture reduction, and bone flap reconstruction.[23] It should be noted that previously, computer-aided navigation was not used to reconstruct the mandible because of its mobility. There are 3 possible solutions to this problem. The first approach is to place the patient in intermaxillary fixation for the CT scan and during the operation, but this is not feasible for transoral surgery. The second method is to place the mandible in centric relation or centric occlusion, either manually or using a dental splint. The mandibular movements are convenient for the operation but undermine the accuracy of intraoperative navigation. In this study we chose the second solution to overcome the drawback related to the mobility of the mandible. Before computer navigation, the mandible was placed in centric relation using arch bar splint fixation, and the mandible location was verified using 3 point landmarks on the mandible. 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 time-consuming, this method has the theoretical advantage of improved accuracy by monitoring the position of the mandible directly, rather than by its relative position to other fixed cranial structures.[8]

Numerous studies have focused on the improvement of computer-aided navigation in mandibular reconstruction, with some success. For example, Casap et al[24] 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 directly attached to the mandible and is specifically designed for implant placement. The navigation error of this system was calculated to be less than 0.5 mm. The second system, the LandmarkX system (Medtronic, Minneapolis, MN), uses a headset frame and requires the mandible to be immobilized during the operation. 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] To our knowledge, our study is the first to evaluate the clinical outcomes of mandibular reconstruction using surgical navigation. We used arch bar splint fixation and multipoint verification of computer-aided navigation to ensure that the mandible was at a constant position relative to fiducial markers.

Mandibulectomy and primary mandibular reconstruction with the fibula flap are extremely time-consuming. These procedures may be expected to be even longer if the position of the fibula flap needs to be repeatedly adjusted and confirmed using CAD and surgical navigation. However, in our study, the mean operative time did not significantly differ among groups A, B, and C. Moreover, a learning curve plotted using the operative times in group C showed that the time required for reconstruction surgical procedures assisted using CAD and surgical navigation decreased with experience. Thus, contrary to expectations, CAD and surgical navigation could reduce the operative time. This is because CAD allows the preoperative determination of the length and angle of the fibula, which can decrease the time required for fibula remodeling.

CAD is helpful to guide the remodeling of the mandibular angle and the placement of the condyle. The combined application of CAD and surgical navigation may result in a more accurate surgical outcome without prolonging the operative time for mandibular reconstruction with free fibula flap.

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