Zygomatic Surface Marker-Assisted Surgical Navigation: A New Computer-Assisted Navigation Method for Accurate Treatment of Delayed Zygomatic Fractures

Yang He, DDS, MD, Yi Zhang, PhD, MD, DDS,† Jin-gang An, DDS, MD,‡ Xi Gong, DDS,§ Zhi-qiang Feng, DDS,|| and Chuan-bin Guo, DDS, MD¶*

Purpose: To describe a new method of zygomatic surface marker navigation to treat delayed unilateral zygomatic fractures.

Patients and Methods: The computed tomography (CT) data for 6 patients were obtained before surgery and imported into the surgical planning software. After 3-dimensional (3D) construction and segmentation, 3D cylindrical-shaped objects in stereolithographic format were placed in position and merged with the data from the fractured segments to mark the area for surface reduction. Data from the unaffected side were used to guide the reduction data for the segments with markers. During surgery, the surface markers were marked by drilling holes in the fractured bones in a process guided by the surgical navigation plan established before osteotomy. The segments were then reduced to the predetermined places using the positions of the hole markers as guides. 3D image comparisons and axial CT measurements were used to evaluate navigation accuracy and bone symmetry.

Results: Six patients with unilateral delayed zygomatic fractures were treated using this approach. The mean deviation between the postoperative 3D images and the reduction navigation plan for the 6 patients was +1.24 mm and −1.4 mm. The mean width deviation between the affected and unaffected sides was 1.28 mm, and the mean eminence deviation was 1.22 mm. All patients were followed up for at least 3 months and experienced no obvious complications.

Conclusions: Zygomatic surface marker-assisted surgical navigation can simplify the navigation planning for surgery and avoid the complex protocols needed to create the surgical templates. The navigation accuracy was acceptable, and all 6 patients obtained good facial symmetry.

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In the midface, the forward projection of the zygomatic complex exposes it to frequent injury. Fractures of the zygomatic complex can lead to displacement of the zygoma and the zygomatic arch, causing such functional and esthetic problems as limitations in mouth opening and facial asymmetry. Reduction and fixation

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

*Attending.

†Professor.

‡Assistant Professor.

§Resident.

||Resident.

¶Professor.

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Address correspondence and reprint requests to Dr Zhang: Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, 22 Zhongguancun Nandajie Street, Haidian District, Beijing 100081, China; e-mail: zhangyi2000@263.net

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Table 1. CLINICAL DATA

Pt. No.	Gender	Age (yr)	Trauma Side	Etiology	Trauma Duration (days)
1	Male	34	Right	MVA	31
2	Female	60	Left	MVA	32
3	Male	41	Left	MVA	36
4	Male	37	Left	Assault	65
5	Male	33	Right	MVA	37
6	Male	52	Right	MVA	246
Mean		42.8			74.5

Abbreviation: MVA, motor vehicle accident; Pt. No., patient number.

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of the fractured bones in the initial surgery can correct most of these problems. However, if treatment is delayed or the reduction is inadequate, secondary deformities can result. Mild esthetic problems can be treated using grafts of alloplastic implants such as porous polyethylene. For severe deformities, however, osteotomy of the fracture lines and repositioning can be required.[1] For delayed zygomatic fractures, the loss of normal anatomic landmarks, caused by the malunion of the fracture lines and resulting remodeling of the bony contour, makes it difficult to determine the correct positions of the zygomatic bones. In such cases, ideal outcomes with satisfactory midface symmetry have been difficult to obtain.[2,3]

The development of computer technologies has made available a large number of computer-assisted surgical techniques to treat oral and maxillofacial trauma. Surgical planning software and computer-generated stereolithographic (STL) models[4-6] have already helped surgeons perform accurate preoperative simulations to obtain ideal 3-dimensional (3D) surgical simulation plans; individually designed esthetic implants can also be fabricated using the available technology.[7] However, successful outcomes depend on the ability to transfer the preoperative surgical plans into the actual procedure. However, before the use of intraoperative navigation, favorable results have been difficult to obtain.

The application of intraoperative navigation systems[8] has brought an effective solution to this problem. However, 1 of the challenges of this method has been that the surface of the zygomatic bone is not regular and lacks obvious anatomic landmarks to guide positioning of the fractured bone during surgical navigation, particularly in cases of delayed fractures.

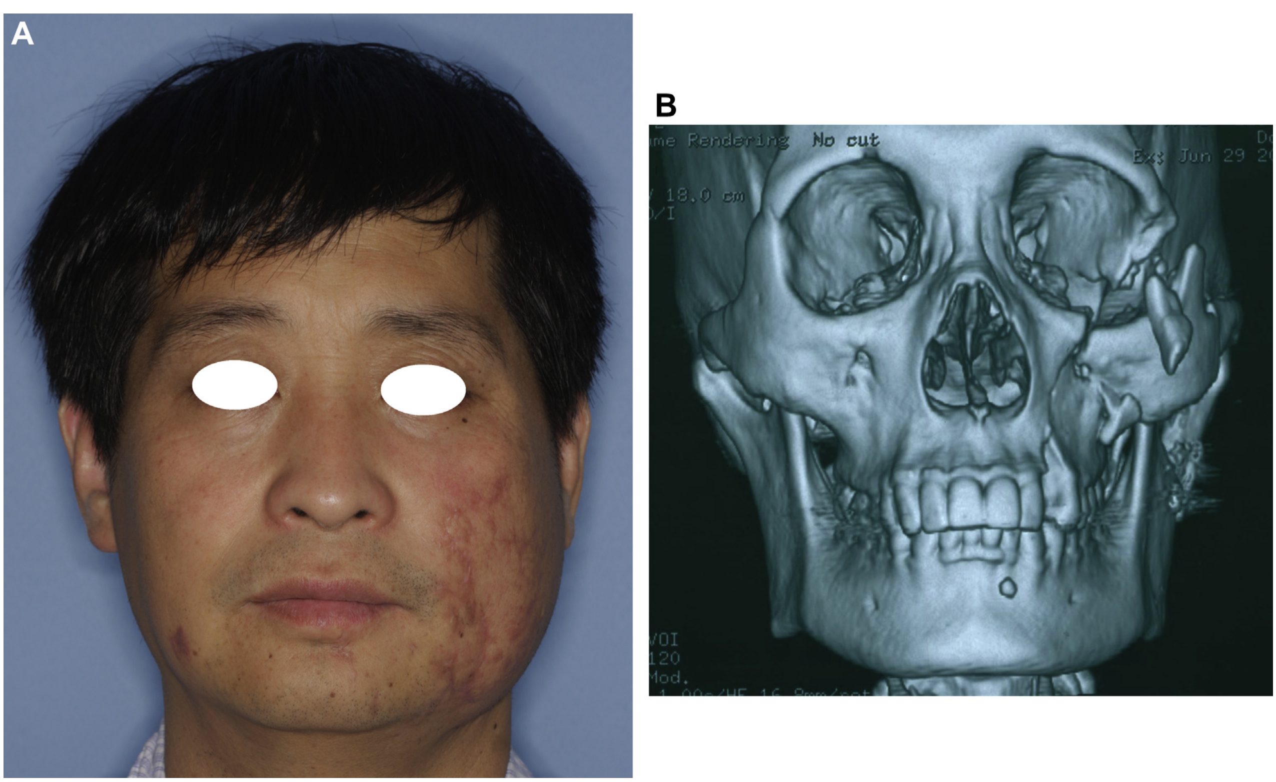

FIGURE 1. The patient had a left zygomatic fracture from a motor vehicle accident, had delayed seeking treatment until 36 days after the injury, and had presented with significant facial asymmetry before surgery. *A*, Preoperative frontal view of the patient. *B*, Frontal view of the 3-dimensional image.

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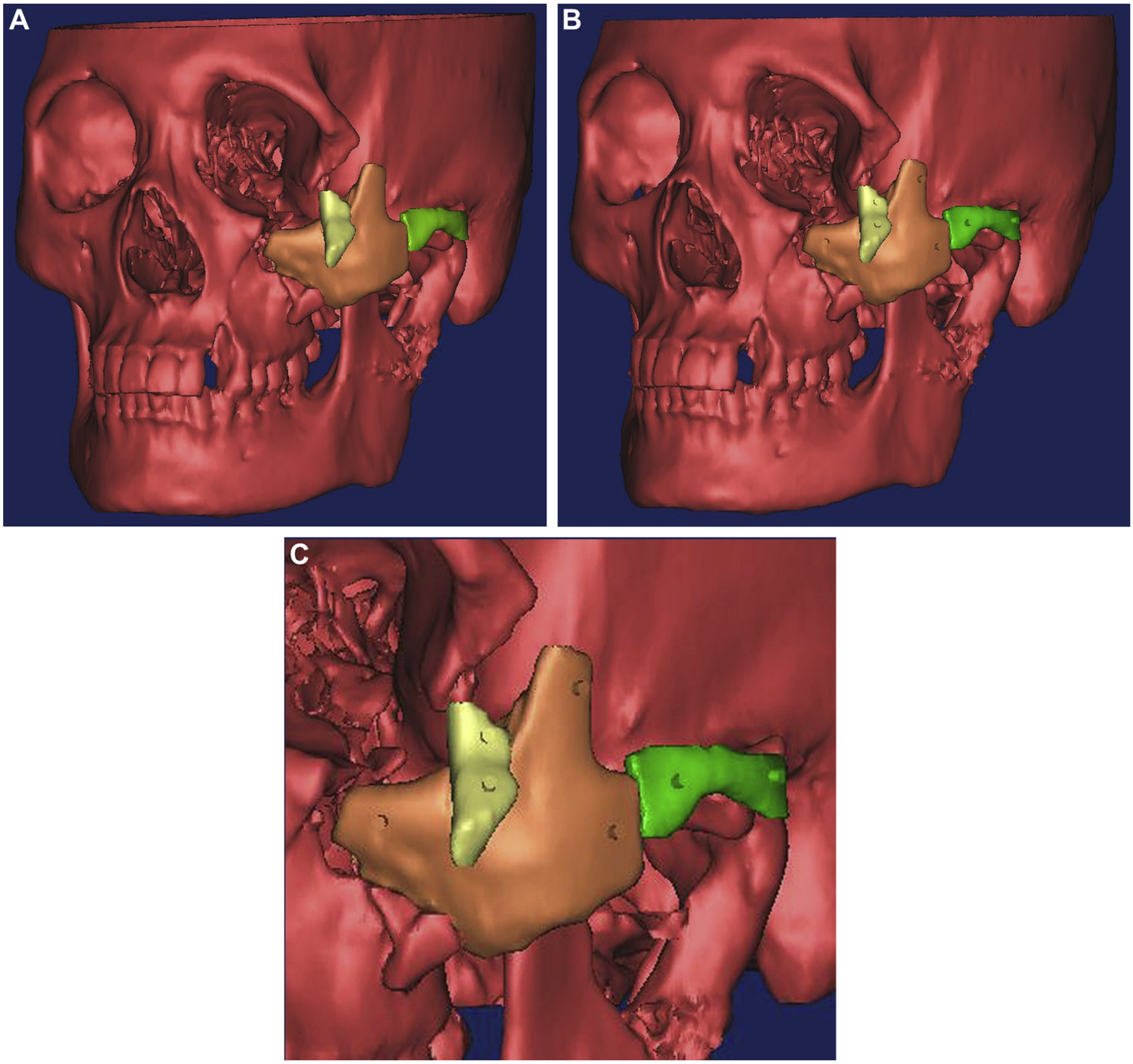

FIGURE 2. Surgical planning. *A*, 3-Dimensional reconstruction and segmentation. *B*, Surface marker creation and location. *C*, Local amplification of surface marker creation and location.

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Several types of navigation methods have been reported for treating zygomatic fractures. Some surgeons have used navigation probes repeatedly during surgery to detect the surface of the zygomatic bone until they can match it to the preoperative plan. This method, although simple to perform, is also somewhat unreliable in achieving the ideal positions. Rapid prototyping techniques for STL model surgery have been reported and have been used with surgical navigation systems. In the latter approach, after surgical software has been used to simulate the surgery and the surgical procedure has been modeled, prefabricated titanium plates are used to locate the position of the zygomatic bone, assisted by surgical navigation. This approach is more accurate than the former technique, but the preoperative preparation is both exceedingly complicated and time-consuming.

However, when reducing delayed zygomatic fractures, the most important factor affecting the results has been the lack of anatomic landmarks. The direct solution would be to create new landmarks artificially on the zygomatic bone surface. The data for surface markers can be implanted into the target bone segments at reasonable positions during the preoperative software design. During the actual surgery, the location of these surface markers can be found using surgical navigation and marked by drilling holes in the zygomatic bone surface before

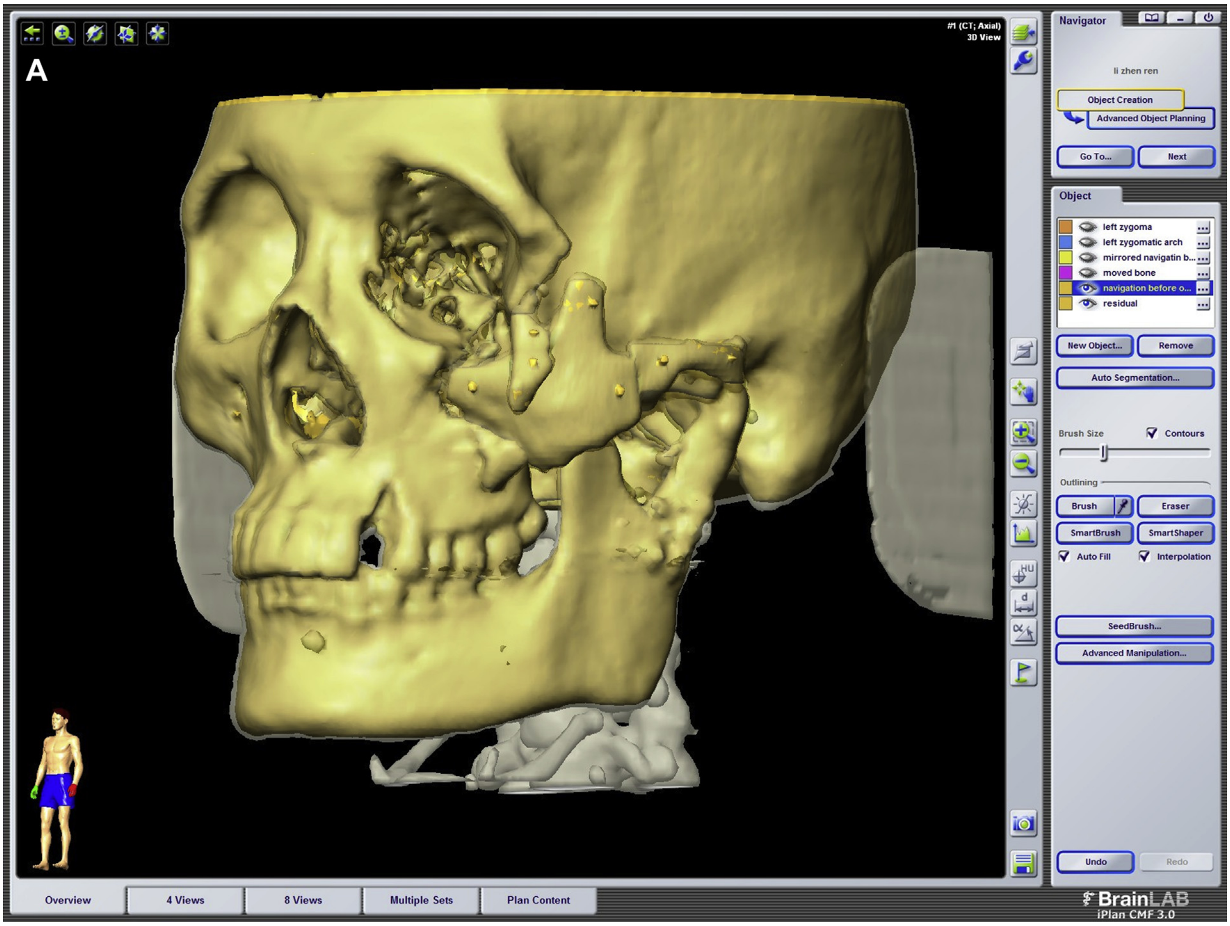

FIGURE 3. Surgical planning using the iPlan software. *A*, The marker location navigation plan (plan 1). **(Fig 3 continued on next page.)**

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osteotomy. This process will help to accurately locate the positions of the target bone segments. In the present study, we have introduced a new method of surgical navigation assisted by zygomatic surface markers and report on its efficiency and accuracy when used in 6 patients with delayed unilateral zygomatic fractures.

Patients and Methods

PATIENTS

Six patients with delayed unilateral zygomatic fractures were treated using the zygomatic surface marker navigation method at the Department of Oral and Maxillofacial Surgery, Peking University School and Hospital of Stomatology, from May to August 2011. Our institutional ethics committee approved the present study (no. IRB00001052-11076), and all patients gave written informed consent to participate. The patients, 5 men and 1 woman, ranged in age from 33 to 60 years (mean 42.8). In all cases, the original treatment had been delayed because of the presence of concomitant injuries or delayed transfer to our institution. The average delay between injury and surgery was 74.5 days (range 31 to 246). Motor vehicle accidents (MVAs) were the main cause of injury in this group (Table 1).

METHODS

All patients underwent preoperative spiral computed tomography (CT), which was repeated 2 weeks after surgery (helix with 1.25-mm slice thickness; Bright Speed 16, GE Healthcare, Buckinghamshire, UK). The CT data were processed and transferred to Surgicase CMF, version 5.0, software (Materialise, Leuven, Belgium) and iPlan CMF software (BrainLAB, Feldkirchen, Germany) using Digital Imaging and Communications in Medicine (DICOM) files on a CD-ROM for preoperative surgical planning and postoperative evaluation. The VectorVision navigation system (BrainLAB) was used for surgical navigation.

We present the protocol we followed for preoperative surgical planning and navigation surgery during the treatment of a participating patient who experienced

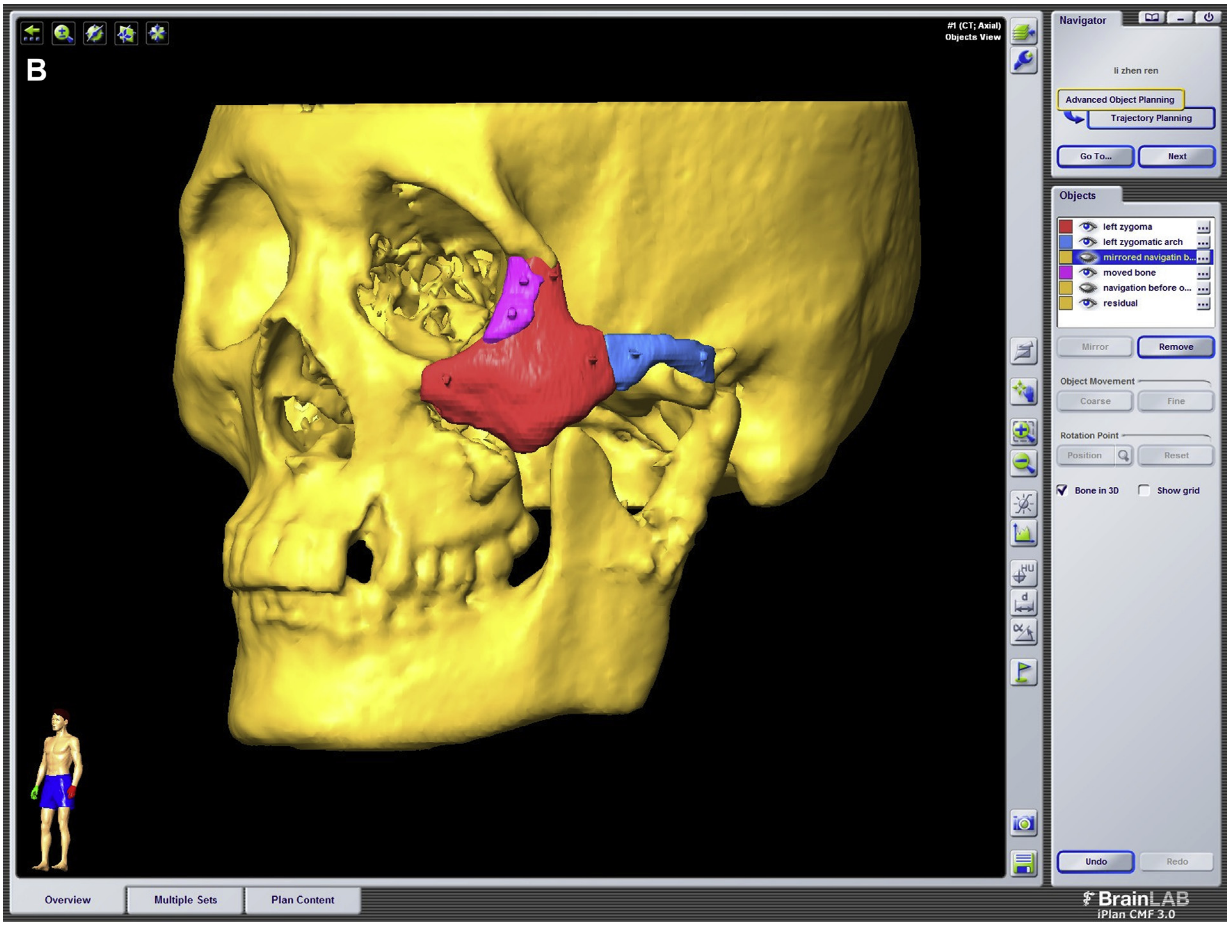

FIGURE 3 (cont'd). *B*, Repositioning of the segments matching the mirrored image to generate the reduction navigation plan of the segments (plan 2). **(Fig 3 continued on next page.)**

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a left zygomatic fracture during an MVA and presented with a 36-day delay between injury and surgical treatment. The patient's left zygoma and zygomatic arch were fractured into 3 main fragments that were significantly displaced and presented as several small bony pieces (Fig 1). The protocol included 2 key parts. First, during preoperative software planning, 3D cylindrical objects in STL format were placed in particular positions and merged with the data from the fractured segments to serve as the surface reduction markers. Second, during the actual surgical procedures, the surface markers were marked by drilling holes in the fractured bones before osteotomy. The segments were then reduced to the planned positions by navigation of the markers.

SURGICAL PLANNING

Surgical planning consisted of 3 steps. First, the surgeon performed 3D-based image construction and segmentation, surface marker creation and location, and segment reduction. Next, 2 surgical navigation plans were developed: the surface marker location navigation plan (plan 1) and the segment reduction navigation plan (plan 2).

Step 1: 3D-Based Image Construction and Segmentation

The preoperative CT data were transferred to Surgicase CMF, version 5.0, software (Materialise) using DICOM files on a CD-ROM. The 3D data of the maxillofacial region were first used for reconstruction (Fig 2A). Using segmentation, the 3 main fractured bony segments that had become separated were colored and individually named (Fig 2A).

Step 2: Surface Marker Creation and Location

The cylinders in STL format were 3 mm in height and 2 mm in diameter and were subsequently replaced and inserted into the 3 segments in their original places (Figs 2B,C). The number of markers was determined to allow for at least 1 marker on each segment, with at least 4 markers for the whole fractured zygomatic bone. Of these, 3 markers were placed, 1 each near the frontozygomatic fissure, the inferior orbital

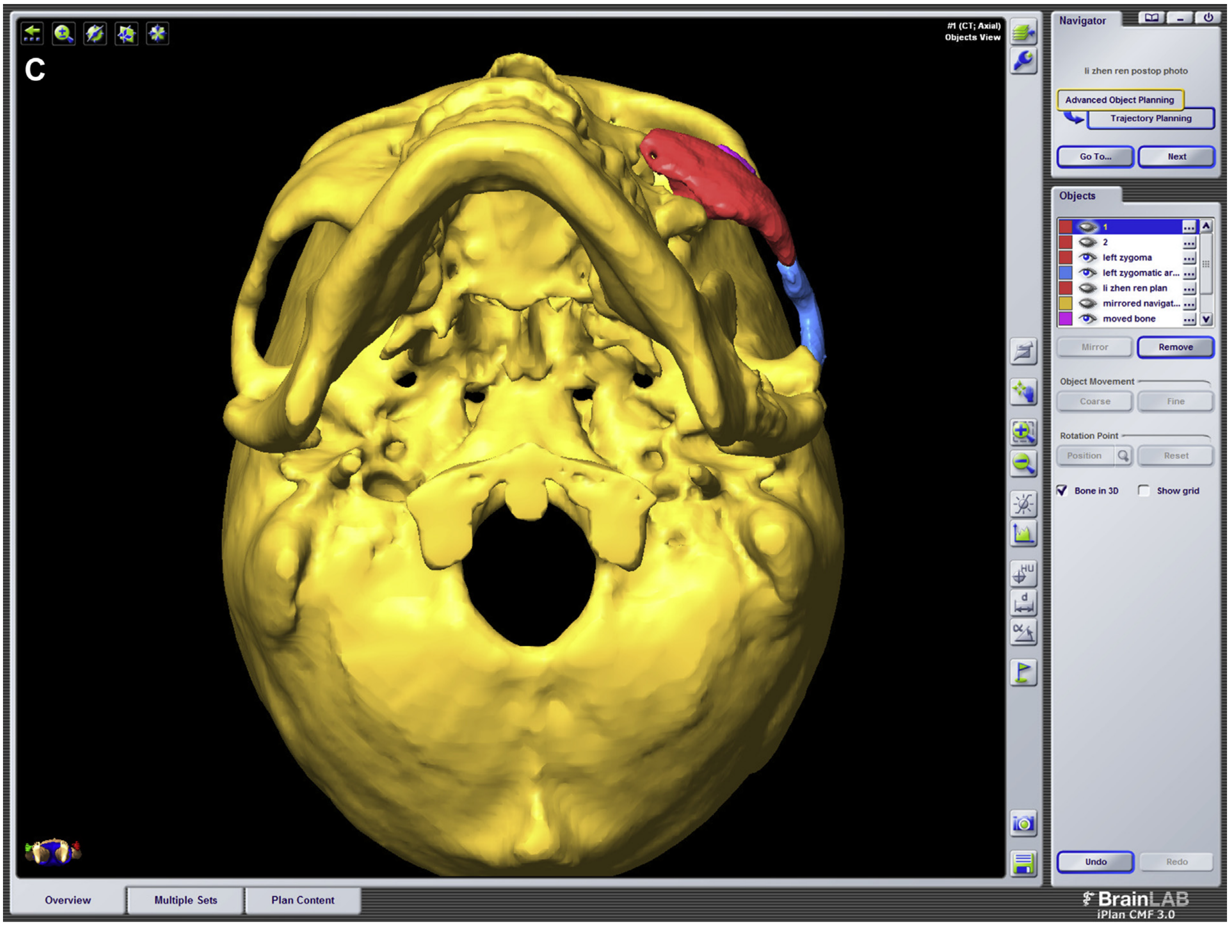

FIGURE 3 (cont'd). *C*, Bottom view of plan 2.

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edge, and the zygomatic arch. The remaining marker was located beside the plane formed by these 3 points. Finally, each segment was merged with its cylinder marker, and the result exported as data in STL format.

The STL data of the segments with surface markers were subsequently imported into the iPlan CMF software (BrainLAB) and merged into 1 object to become the surface marker location navigation plan (plan 1; Fig 3A).

Step 3: Segment Reduction

Subsequently, the iPlan CMF software mirrored the 3D object on the normal side to the affected side. The facial midline was set according to the line that passes through the nasion, the center of the sella, and the center of the line that joins the left and right external acoustic foramens. Because actual human skulls are not completely symmetric, the mirrored normal half was adjusted to match the contour of the unaffected bone on the fractured side. The fractured segments with markers were subsequently repositioned to match the contour of the mirrored normal object, and reduction navigation plans were generated for the segments (plan 2; Fig 3B,C). Finally, the whole surgical plan was transferred to the VectorVision navigation system before surgery.

Navigation Surgery

The VectorVision navigation system was used for intraoperative navigation. After the induction of general anesthesia, a reference frame with 3 light-reflecting balls was rigidly fixed to the patient's skull to identify the patient's position. The registration was then completed through facial surface scanning using a Z-touch wireless laser pointer. The software automatically verified the registration accuracy of the surgical area in all 6 patients, and the registration error was less than 0.7 mm in all cases.

The fractured zygoma and zygomatic arch were then exposed using the subciliary, coronal, and intraoral approaches, which were primarily used in this group of patients. The operations were conducted carefully to avoid excess pressure on the fractured bones. After exposure of the fractured bones, navigation probes were used to test for displacement of the fractured bones, especially for small bony fragments.

A

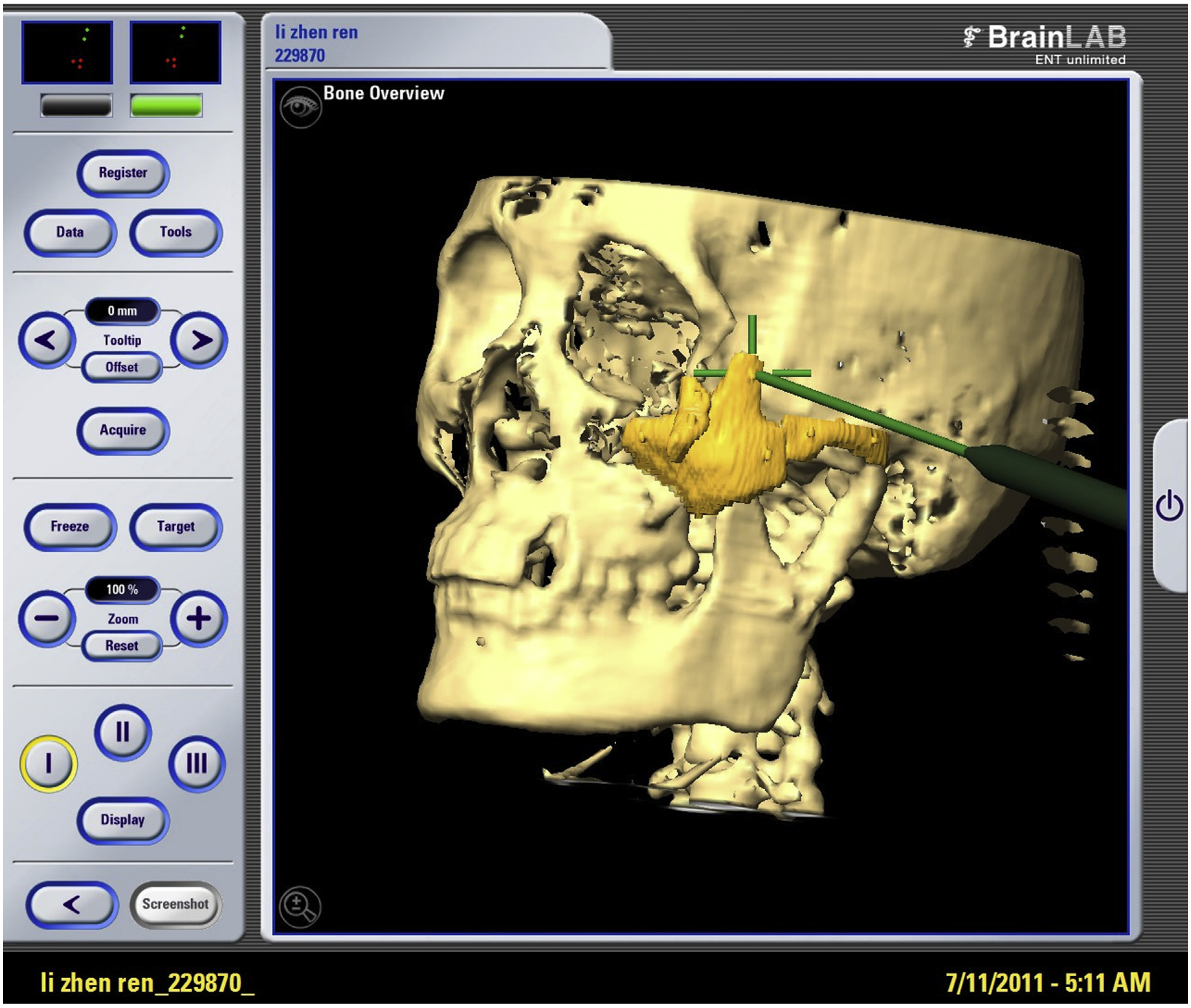

FIGURE 4. Navigation surgery. *A*, Location of the surface marker guided by plan 1 before osteotomy. **(Fig 4 continued on next page.)**
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Using navigation plan 1, all reduction markers were produced by drilling holes in the fractured bones before osteotomy (Fig 4A,B). After osteotomy, the fractured segments were released and then reduced to the planned places according to a given sequence of height, projection, and width of the zygoma and zygomatic arch by checking the positions of the hole markers, guided by plan 2 (Fig 4C,D).

The height of the zygoma was initially reduced by locating the surface marker (on plan 2) that was closest to the frontozygomatic fissure. Titanium microplates (Synthes, Oberdorf, Switzerland) were used to rigidly fix the bony segments. The projection and width of the zygoma and zygomatic arch were subsequently reduced, guided by the surface markers on the inferior orbital edge and the zygomatic arch. Finally, the position of all surface markers was checked against plan 2 to assess the accuracy of the reduction. The fractured bones were rigidly fixed (Fig 5), and surgical wounds were closed at the end of surgery.

EVALUATION

All patients underwent CT scans 2 weeks after surgery and were followed up for at least 3 months (Fig 6). Two methods were used to evaluate the navigation accuracy and facial symmetry.

First, the accuracy of navigation surgery was evaluated by comparing the postoperative 3D images with plan 2 (Fig 7). The postoperative 3D images and plan 2 were created as STL files, imported into Geomagic Qualify, version 12.0 (Geomagic, Morrisville, NC), and then superimposed, one on the other. The outside surfaces of the zygoma and zygomatic bone from the 2

B

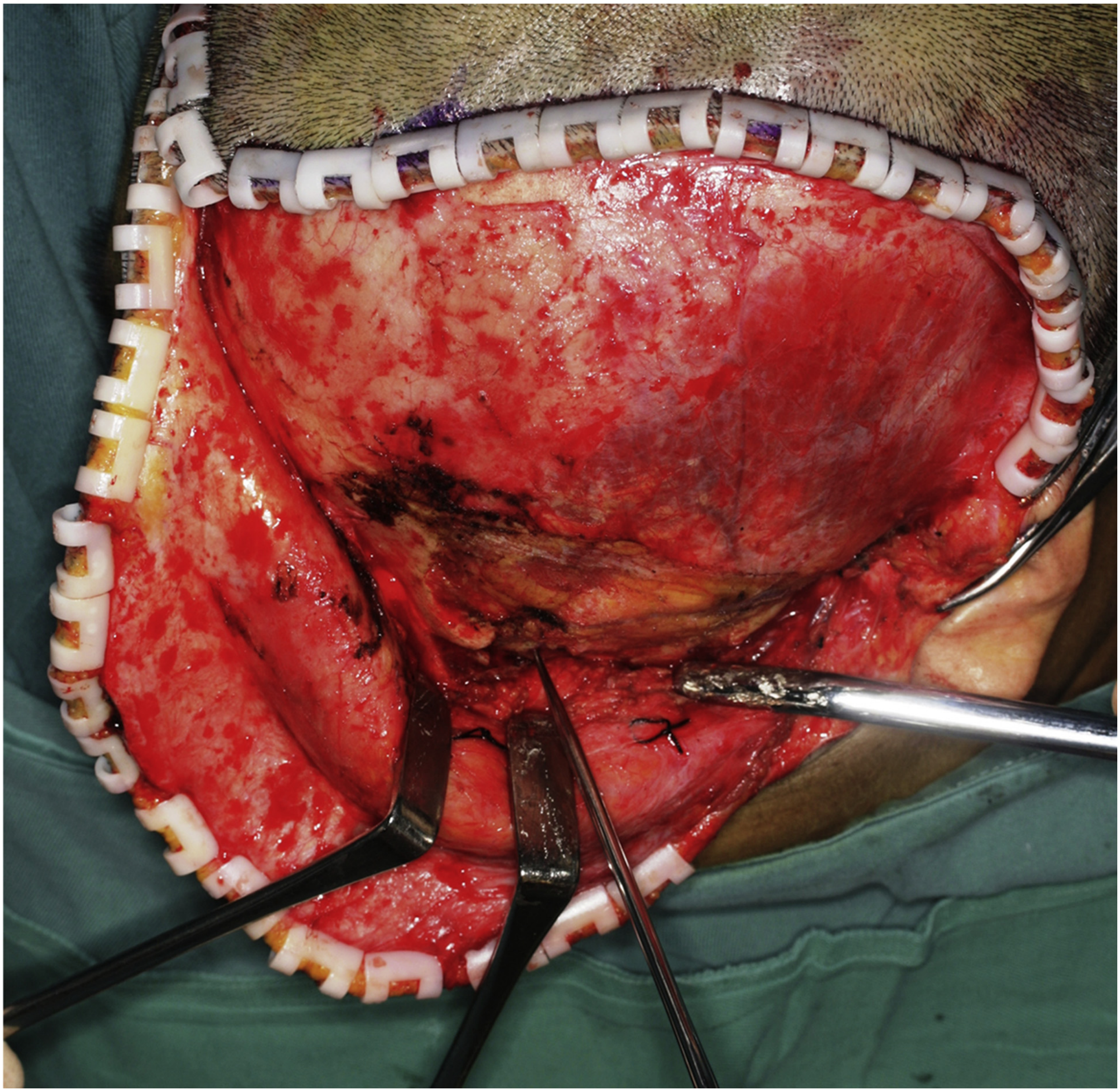

FIGURE 4 (cont'd). *B*, Location of the marker on the fractured bone guided by plan 1 and drilling holes for marking. **(Fig 4 continued on next page.)**

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files were selected for comparison. The program automatically recognizes the corresponding points from the 2 files and highlights the superimposed image with different colors according to the distance between the corresponding points. After the comparison, a color-graded error map was generated to show the matching deviation between the 2 files, with each grade of deviation indicated by a specific color. The distances from the corresponding points in the 2 files were also measured and analyzed automatically for a comparison report. In that report, positive data (+) indicated that the points in the postoperative file were outside those points in the plan 2 file. Negative data (−) indicated that the points in the postoperative file were inside the same points in the plan 2 file. Average deviations were used to evaluate the navigation accuracy in the present study. For instance, the average deviation for the presented patient was +1.115 mm and −1.194 mm (Fig 7).

Second, the bilateral symmetry of the zygoma and zygomatic arch bone was evaluated using CT measurements (Fig 8). Distances from the overall high points of

C

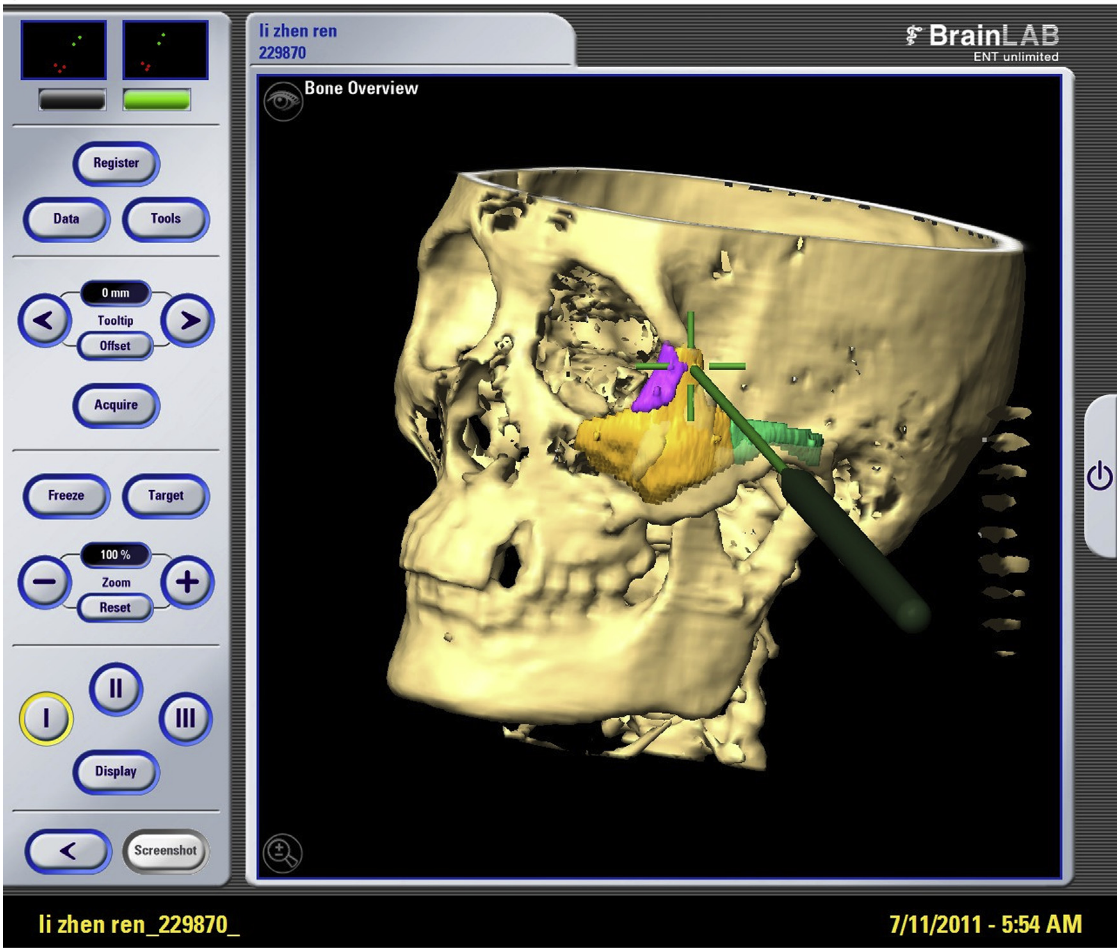

FIGURE 4 (cont'd). *C*, Repositioning of the markers guided by plan 2 after osteotomy. **(Fig 4 continued on next page.)**

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the zygomatic contours to the intersection points between the midline and the anterior borders of the skull base were measured and compared to assess the symmetry of the malar eminence (Fig 8A). Distances from the midline to the widest point of the zygomatic arch on each side were measured on axial CT scans. The deviations between the affected and unaffected sides were calculated to assess the symmetry of the facial width (Fig 8B). The eminence deviation for the presented patient was 1.2 mm and the width deviation was 1.7 mm.

Results

All 6 patients were treated according to the described procedure. In these 6 patients, the average deviation between the postoperative 3D images and the reduction navigation plan was +1.24 mm and −1.4 mm. The average width deviation between the affected and unaffected sides was 1.28 mm, and the average eminence deviation was 1.22 mm (Table 2).

All 6 patients were followed for at least 3 months, and facial symmetry was considered satisfactory after surgery. No obvious complications were found in this patient group.

Discussion

For delayed zygomatic fractures and secondary posttraumatic midface deformities, the loss of normal anatomic landmarks, caused by malunion of the fractures and remodeling of the bony contours, will make it difficult to reposition fractured segments to their ideal positions. The use of surgical planning software and computer-generated STL models can help surgeons achieve accurate preoperative surgical simulations. However, transferring the preoperative surgical plans to the actual surgical procedures has remained problematic.

Since the mid-1990s, surgical navigation has been increasingly used to treat craniomaxillofacial malformations, and it has emerged as an effective technique

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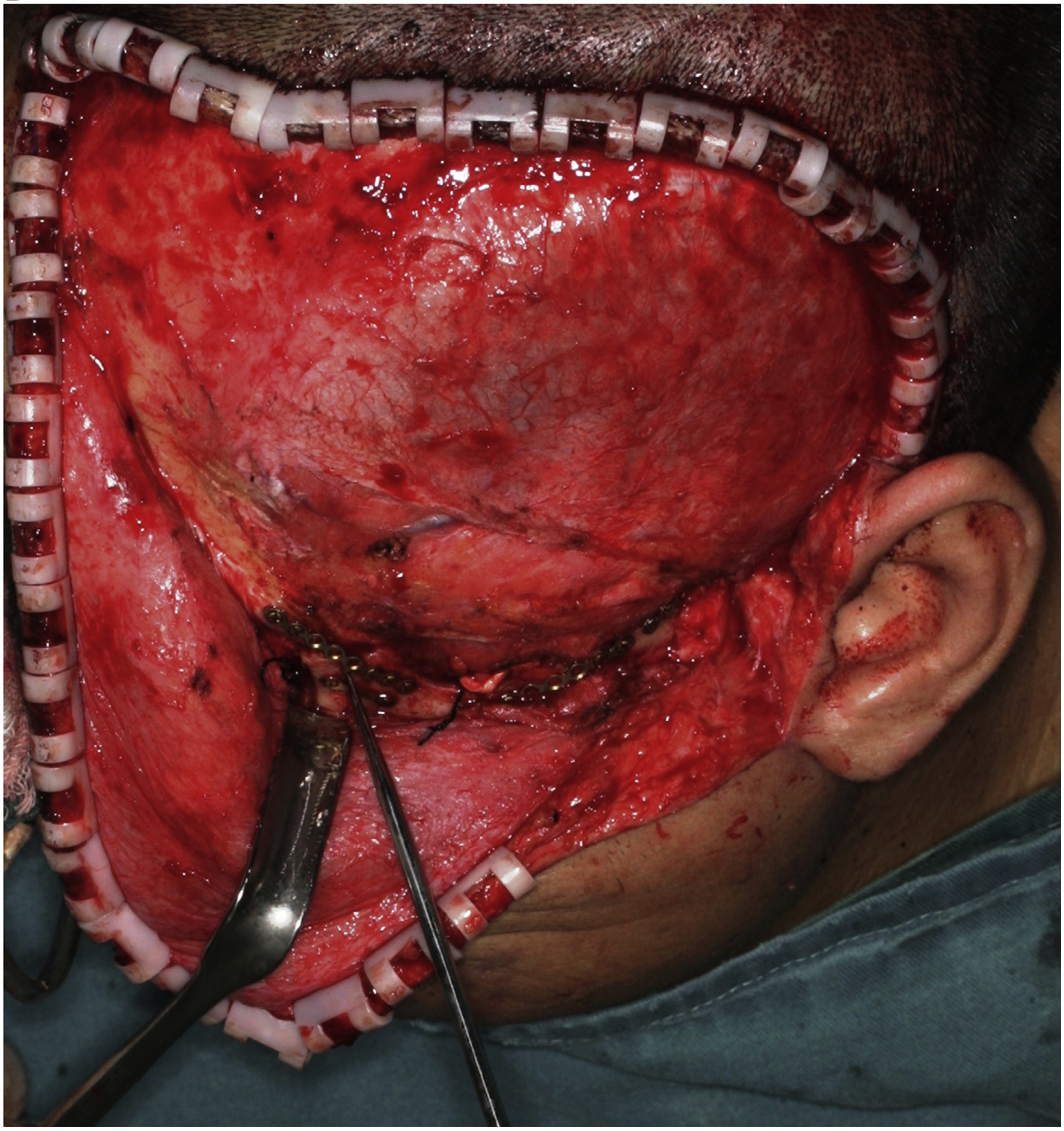

FIGURE 4 (cont'd). *D,* Location of the segment guided by plan 2.

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to address the challenges of this type of injury.[8] Various studies have reported the 3 main classes of protocols.

Zygomatic surface checking, perhaps the most commonly used approach for intraoperative navigation, is performed as described in the following protocol.[9-13] In the preoperative plan, the fractured segments are repositioned into the ideal positions, which mirror the images of the normal side that is usually used. During the actual surgery, the fractured zygoma is gradually repositioned to the planned position by repeatedly checking its surface and comparing it with the surgical plan. In this method, the preoperative surgical plan is easy to develop, but during surgery, the surgeon must check the position many times. However, the zygomatic surfaces are not regular, making it difficult and time-consuming to find the planned positions, especially when the bone has multiple fractures.

Another approach uses intraoperative navigation combined with prebent surgical templates on STL models.[5,6,14] Before surgery, STL models are made according to the CT data. Osteotomy and repositioning of the zygoma are then simulated on the STL model, to which surgically guided templates (eg, osteosynthesis plates) are prebent and adjusted. The CT data from the operative model can be obtained before surgery and used to navigate the template positions. The

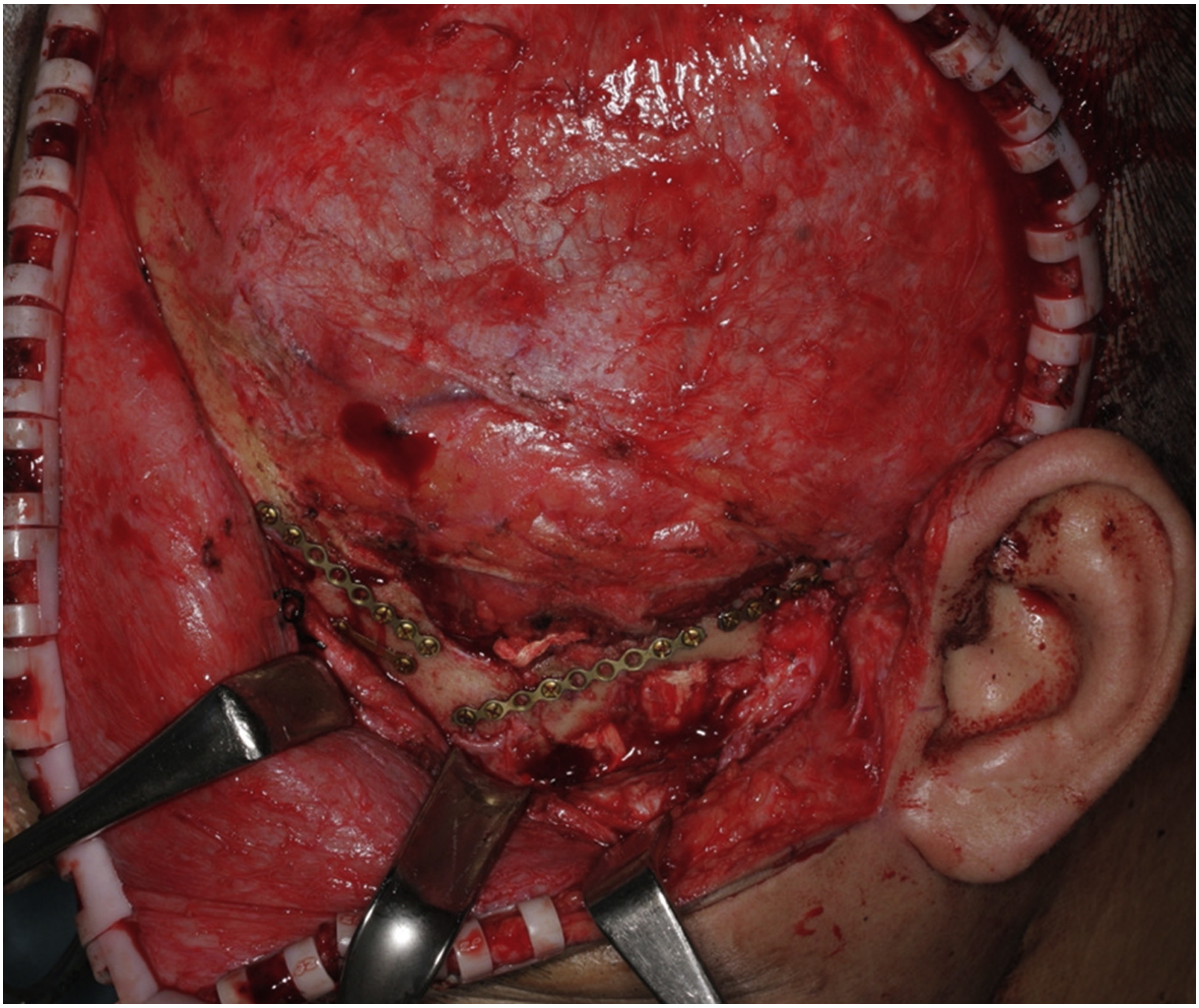

FIGURE 5. After repositioning, the fractured bones were rigidly fixed using titanium plates.

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intraoperative repositioning of the fractured zygomatic bones is guided by navigation and the prebent templates. However, templates such as titanium plates cannot be fabricated, and, in any case, they would not be able to be bent accurately enough to completely match the bone surface. Thus, errors will exist between the position indicated by the templates and surgical navigation. Also, creating templates before surgery is very time-consuming.

Finally, the most accurate method described to date might be that reported by Baumann et al,[15] Klug et al,[2] and Xia et al,[3] known as the "reversed approach" or "point-to-point protocol." In this approach, surgery is simulated on STL models or visualized using computer software. After segmentation and repositioning of the displaced zygoma, fixation plates are bent and screwed onto the 3D image using computer software. The reduced zygoma is then returned to its original position, and the positions of the screw holes are saved and imported to the surgical navigation system. Intraoperatively, the navigation system is used as a guide to drill the screw holes before osteotomy. After osteotomy and reduction, the displaced bone is fixed using the prebent plates. This approach has demonstrated great accuracy. Klug et al[2] measured the distance between the screw positions in the models and those in the patients and found a mean distance of 1.1 ± 0.3 mm for 44 screws. However, the complicated surgical plan requires a correspondingly long preoperative preparation time.

As previously mentioned, the location of the screw holes using point-to-point navigation might be the most useful and accurate approach for treating delayed zygomatic fractures; however, it is still very complicated. Nevertheless, the most important factor affecting the results, when reducing delayed zygomatic

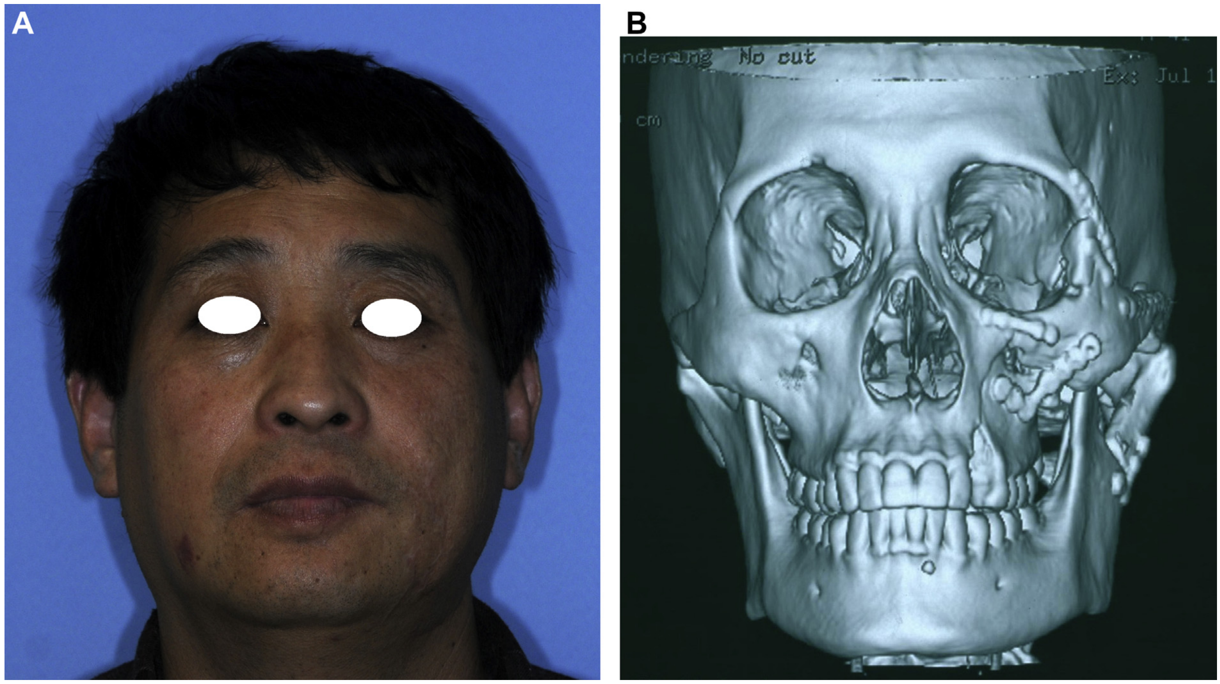

FIGURE 6. Photographs of the patient 3 months postoperatively and the postoperative 3-dimensional images showed satisfactory facial symmetry. *A*, Frontal view of the patient. *B*, Frontal view of the 3-dimensional image.

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fractures, is the lack of anatomic landmarks. The direct solution would be to artificially create new landmarks on the surface of the zygomatic bone, a strategy described in the present study.

Using geometry, the location of 4 points on a 3D object can determine the position of the object. The zygomatic bone gives the cheek its prominence, including the eminence, height, and width, and we need locate only 4 points on the zygomatic bone to determine its position. Holes drilled on the displaced bones can be used as surface landmarks for repositioning, as described by Baumann et al,[15] Klug et al,[2] and Xia et al.[3]

In this method, at least 4 markers are made on the 3D object to position the whole fractured zygomatic bone during preoperative planning; 3 are critical. The critical markers should be located at places close to the frontozygomatic fissure, the inferior orbital edge, and the zygomatic arch, representing the height,

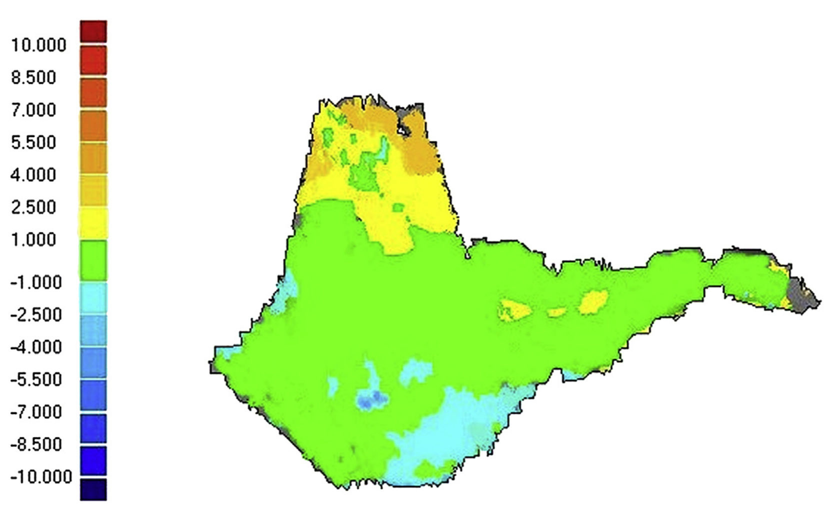

FIGURE 7. Accuracy evaluation. The color map of the 3-dimensional comparison between the postoperative 3-dimensional image and plan 2 is shown; the average deviation was +1.115 mm and −1.194 mm.

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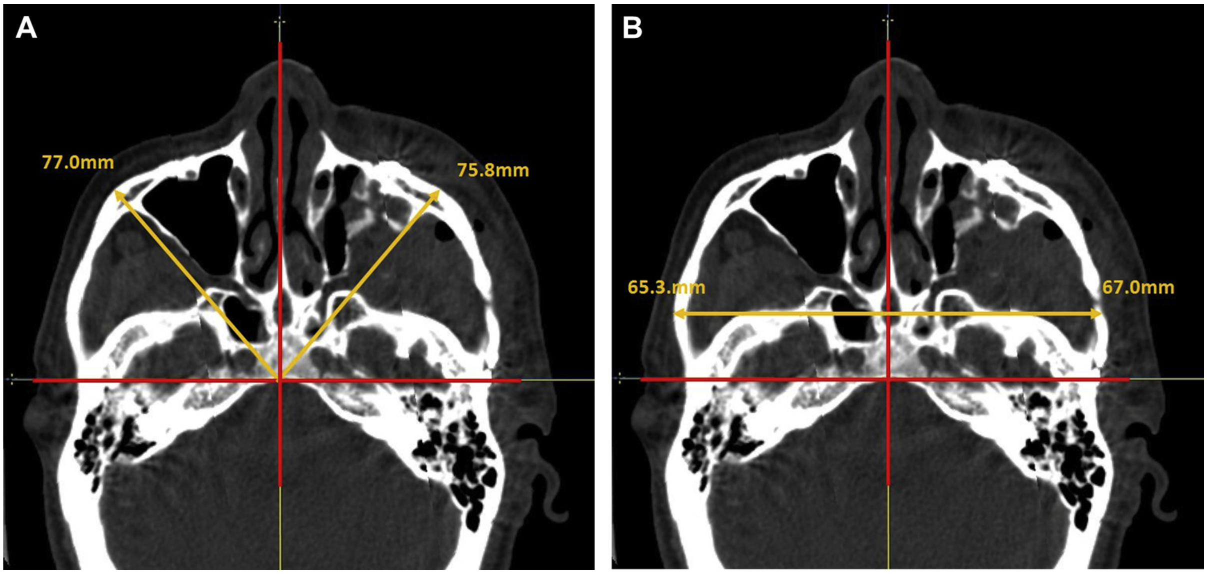

FIGURE 8. Symmetry evaluation using axial computed tomography scans. *A*, Eminence measurement. *B*, Width measurement.

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eminence, and width of the midface, respectively. The other markers, located beside the plane formed by these 3 points, serve to check the accuracy. This approach requires simpler preoperative planning than the previous approaches. In addition, this method requires neither surgical templates nor STL models.

The deviation between the preoperative design and the actual surgical results has been previously measured. Yu et al[11] found the maximal deviation to be less than 2 mm. Klug et al[2] reported a mean deviation of 1.1 $\pm$ 0.3 mm. In the present study, a comparison of the postoperative 3D objects and the surgical plans showed that satisfactory accuracy was obtained in all 6 patients, with a mean deviation of +1.24 mm and −1.4 mm. These tolerances were similar to the results reported by Yu et al[11] and Klug et al.[2] In another study, Ogino et al[12] measured the distances from the midline at several points in 6 patients using postoperative CT scans. The mean difference between the left and right was 1.6 mm.[12] In our study, CT evaluation of the reductions showed a mean width deviation of 1.28 mm between the affected and unaffected sides and a mean eminence deviation of 1.22 mm, indicating good symmetry.

In our group of patients, the delay for the sixth patient between injury and surgery was 246 days, much longer than that for the other patients. Because of bone healing and remolding, the zygoma and zygomatic arch had become deformed and had stabilized in the wrong position. Therefore, surgical treatment seemed more difficult than in the cases in which the bones had not healed completely. Formal zygomatic osteotomies were performed to correct the facial asymmetry, and

Table 2. RESULTS FROM POSTOPERATIVE EVALUATION

	Eminence (mm)			Width (mm)			Accuracy Measurement (mm)	
Pt. No.	Unaffected Side	Affected Side	Deviation	Unaffected Side	Affected Side	Deviation	+	−
1	81.8	79.9	1.9	69.1	67.9	1.2	1.13	0.78
2	82.7	84.5	1.8	63.2	65.1	1.9	0.9	1.56
3	77	75.8	1.2	65.3	67	1.7	1.12	1.19
4	86.1	86.3	0.2	72.2	72.4	0.2	0.92	1.89
5	86.5	84.9	1.6	73.8	73	0.8	1.55	1.77
6	83.6	84.2	0.6	69.1	71	1.9	1.83	1.18
Mean			1.22			1.28	1.24	1.4

Abbreviation: Pt. No., patient number.

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this navigation method has been shown to be effective in improving surgical accuracy. However, these types of zygomatic deformities could also be treated by grafting of esthetic implants, especially those fabricated preoperatively using the computer-aided design and computer-aided manufacturing technique.[7]

In the present study, the method was used to treat only delayed unilateral zygomatic fractures, because the images of the unaffected side could be mirrored to the affected side and used as a reference for reduction, an approach often used. Delayed bilateral zygomatic fractures are more difficult to treat owing to the loss of reference data. Lubbers et al[16] even considered a "bilateral fracture of lateral midface" to not be an indication for surgical navigation because of the loss of the reference side. However, we believe that bilateral fractures of the lateral midface could require even more use of surgical navigation, because of the difficulty in deciding on the position of the fractured bones using personal judgment alone. Some methods allow for the creation of surgical plans without the reference side. In the case of bilateral factures, the side that is easy to reposition can be reduced first. Then, using its mirror image, the other affected side, with the more complex fracture, can be subsequently repositioned to achieve facial symmetry. When bony defects accompany complex bilateral fractures, therapy is required, not only to reduce the fracture, but also to rebuild the midface, a very challenging problem for surgeons. In these cases, soft tissue simulation[17] and 3D facial databases of normal subjects[18-20] could be helpful.

In conclusion, in the present study, a new approach of surface marker navigation was used to treat 6 patients with delayed unilateral zygomatic fractures. Zygomatic surface marker-assisted surgical navigation can simplify surgical planning for navigation surgery and avoid the complex protocols required for surgical templates. Navigation accuracy was also satisfactory, and good facial symmetry was obtained in all 6 patients.

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