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Treatment of skeletal open bite using a navigation system: CAD/CAM osteotomy and drilling guides combined with pre-bent titanium plates

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Abstract. Severe skeletal open bite associated with posterior vertical maxillary excess and mandibular deformity is considered a difficult problem in orthodontic and surgical treatment. This study used a navigation system for the correction of severe skeletal open bite in order to accurately transfer the virtual plan to the actual operation and achieve precise rigid internal fixation in bimaxillary osteotomies of the jaws. Twelve patients with a severe skeletal open bite associated with vertical maxillary excess and mandibular deformity were recruited. All patients underwent Le Fort I osteotomy and bilateral sagittal split ramus osteotomy with the guidance of this navigation system. Computed tomography and cephalometric examinations were performed to evaluate the correction of the deformity. Deviations between the simulated plan and actual postoperative outcome were measured to determine the precision of the surgery. Satisfactory and stable results were achieved in all patients postoperatively, without complications or relapse during follow-up. Photographs and cephalometric evaluations showed that the facial profile and occlusion were improved. Assessment of the deviations between the simulated plan and actual postoperative outcome showed that the navigation system can precisely transfer the virtual plan to the actual operation. The results suggest that the navigation system can accurately transfer the virtual plan to the actual operation during bimaxillary jaw osteotomies, without relapse, in patients with a severe skeletal open bite.

Key words: severe skeletal open bite; CAD/CAM; osteotomy and drilling guides; pre-bent titanium plates; orthognathic surgery.

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A skeletal open bite malocclusion in adults is basically a vertical dentofacial problem caused by excessive vertical development of the maxilla or shortening of the mandibular ramus. Either of these tends to produce a downward–backward rotation of the mandible that increases the anterior face height and separates the anterior teeth[1]. Maxillary surgery is not sufficient when it comes to a severe vertical discrepancy caused by both maxillary and mandibular deformities. Bimaxillary osteotomies of the jaws together with orthodontic treatment may provide better results[2,3]. An accurate surgical plan executed with precision during the real surgery is essential for the success of bimaxillary osteotomies of the jaws, especially repositioning of the maxillary and condylar segments[4].

A technique using computer-aided design and computer-aided manufacturing (CAD/CAM) intermediate splints has recently been developed as an alternative to the traditional methods, with the aim of increasing the accuracy of the bimaxillary osteotomies of the jaws[5]. The osteotomy and repositioning of the maxilla is maintained using the guiding templates, which are aligned to the skull base or connected to the maxilla rather than relying on the mandible. Errors in the traditional model surgery procedure, such as rotation of the mandible, are partly reduced with the help of CAD/CAM wafers[6,7].

Postoperative malocclusions resulting from inaccurate execution during the operation are common and difficult problems in the treatment of severe skeletal open bite. The majority of CAD/CAM techniques now focus on aiding the surgical design and guiding the osteotomy, and ignore placement of the titanium plates. With the development of CAD and rapid prototyping (3D-print) technology, customized three-dimensionally printed titanium plates and individual pre-bent titanium plates can be used to reposition the maxilla during orthognathic surgeries[8,9]. However, no article has reported the use of this type of navigation system for the treatment of severe skeletal open bite.

This study applied the navigation system using CAD/CAM osteotomy and drilling guides combined with pre-bent titanium plates. It was hoped that the virtual orthognathic plan could be precisely transferred to the actual operation using this system and that precise rigid internal fixation (RIF) could be achieved in bimaxillary osteotomies of the jaws for the correction of severe skeletal open bite.

Materials and methods

Patients

The study was conducted in the West China Hospital of Stomatology of Sichuan University and was approved by the Ethics Committee of the West China School of Stomatology, Sichuan University. Twelve patients diagnosed with a severe skeletal open bite were recruited from patients who attended the West China Hospital of Stomatology, Sichuan University during the period June 2014 to August 2017. All patients were informed about the purpose of the study and written consent was obtained.

The inclusion criteria included: (1) patients without systemic diseases between 18 and 35 years old, (2) patients scheduled to undergo two-jaw orthognathic surgery to treat a severe skeletal anterior open bite, and (3) patients diagnosed with a severe skeletal open bite: S–Go/N–Me <62%, N–ANS/N–Me <45%. Of the 12 patients, seven were male and five were female; they ranged in age from 20 to 31 years. Their open-bite distance vertically ranged from 6 mm to 18 mm. All patients underwent Le Fort I osteotomy and bilateral sagittal split ramus osteotomy (BSSRO), and accepted pre- and postoperative orthodontic treatment.

Virtual surgery and design of the navigation system

All patients were asked to be relaxed and maintain a gentle bite position during computed tomography (CT) scanning. All three-dimensional (3D) images were captured using a Philips Brilliance 16 CT scanner (Philips Healthcare, Best, The Netherlands) with the following parameters: 120 kV, 282 mA, and 26.3-s scan time. The slice thickness was set at 0.16 mm and the voxel size was 0.65 mm^3. The 3D images were transformed to DICOM format (Digital Imaging and Communications in Medicine) and reconstructed with Mimics software 10.0 (Materialise Inc., Leuven, Belgium). Data for the virtual titanium plate models were obtained from Zimmer Biomet (Zimmer Biomet Holdings Inc.,Campbell, California, USA).

First, a simulated operation was performed on the jaws reconstructed from the CT. The maxilla received a Le Fort I osteotomy and the mandible received a BSSRO. The upper and lower jaws were then repositioned into the required position. In the process of simulation, both sides of the condyles were always kept in their initial position. However, if a large gap or interference existed between the proximal segment and distal segment when reaching the ideal position, the proximal segment would be appropriately rotated using the condyle vertex as the centre of rotation. After the surgical simulation, the virtual plate models were bent to make sure they were adapted to the postoperative virtual bone surfaces that had been repositioned in the desired position.

Accordingly, the locations of the screw holes could be marked on the bone surface using the holes in the titanium plate model (Fig. 1A, E). The virtual titanium plates were then removed, and the maxillary and mandibular segments containing the location information of the screw holes were moved back to their original positions. At this time, the positions of the screw holes on the bone surface before the osteotomies were determined. Depending on the positions of the screw holes, drilling guide templates were designed on the virtual bone surface on each side of the maxilla and mandible (Fig. 1B, F). At the same time, the holes were generated perpendicular to the bone surfaces on the templates by the indication of virtual plate screw holes (Fig. 1B, F). The osteotomies were also marked on the templates (Fig. 1C, G). Intermediate and final wafers were then created (Fig. 1G), in addition to the arms connected to the guiding templates and splints (Fig. 1C, G). The cavity block templates were generated by offsetting surfaces of the virtual pre-bent titanium plates (Fig. 1D, H). The heights of the guiding templates were 2.5 mm. All of these were fabricated via rapid prototyping technology. The titanium plates were manually pre-bent to fit the cavity blocks.

The navigation system in this study consisted of two components: the CAD/CAM osteotomy and drilling guides and the pre-bent titanium plates (Fig. 2). The pre-drilled screw holes, the osteotomies, and the pre-bent titanium plates in this system contained the entire details of the surgical plan.

Transfer of the virtual plan to the operating room

The surgical procedure is simply the opposite sequence of the virtual design (Fig. 3). After attaching the osteotomy guide to the bone surface with the help of the wafer, the screw holes were pre-drilled through the predetermined holes on the guides. The guides were then fixed. Following this, the osteotomy was performed under the guidance of the osteotomy lines. Next, the osteotomy guides and the wafers were removed. The pre-bent plates were then correspondingly

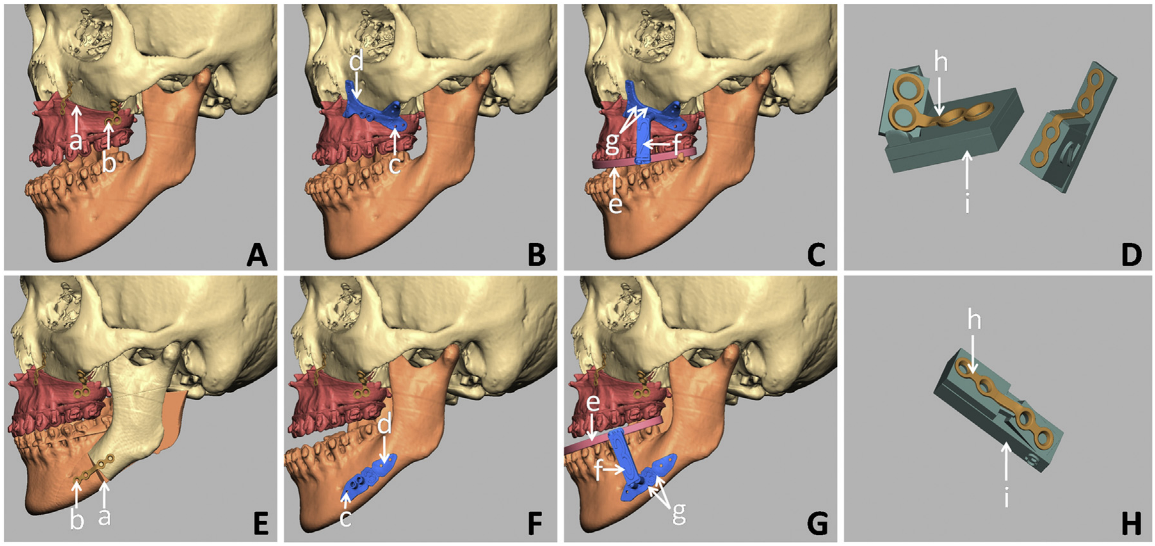

Fig. 1. The design process for the navigation system. Images A and E show the virtual osteotomies and bending of the virtual plates to make sure they are adapted to the bone surface; ‘a’ indicates the osteotomy line and ‘b’ indicates the screw holes on the virtual plate. Images B and F show removal of the virtual plates and movement of the bone segments back to their original positions, generation of the virtual osteotomy and drilling templates on the bone surface, and marking of the screw holes and osteotomy lines on the templates; ‘c’ indicates the screw holes and ‘d’ indicates the virtual osteotomy and drilling template. Images C and G show the creation of the intermediate wafers and the connection arms; ‘e’ indicates the intermediate wafer, ‘f’ indicates the connecting arm, and ‘g’ indicates the osteotomy lines. Images D and H show the cavity block templates; ‘h’ indicates the virtual pre-bent plates and ‘i’ indicates the cavity blocks of the plate.

installed by placing the screws in the related holes.

The maxilla usually needs a clockwise rotation when treating a severe skeletal open bite patient. In this situation, the posterior portion of the maxilla requires partial removal of the bone to avoid interference. Bone removal in the posterior maxilla was performed according to the interference of the bone in the preoperative simulation and the position of the titanium plate

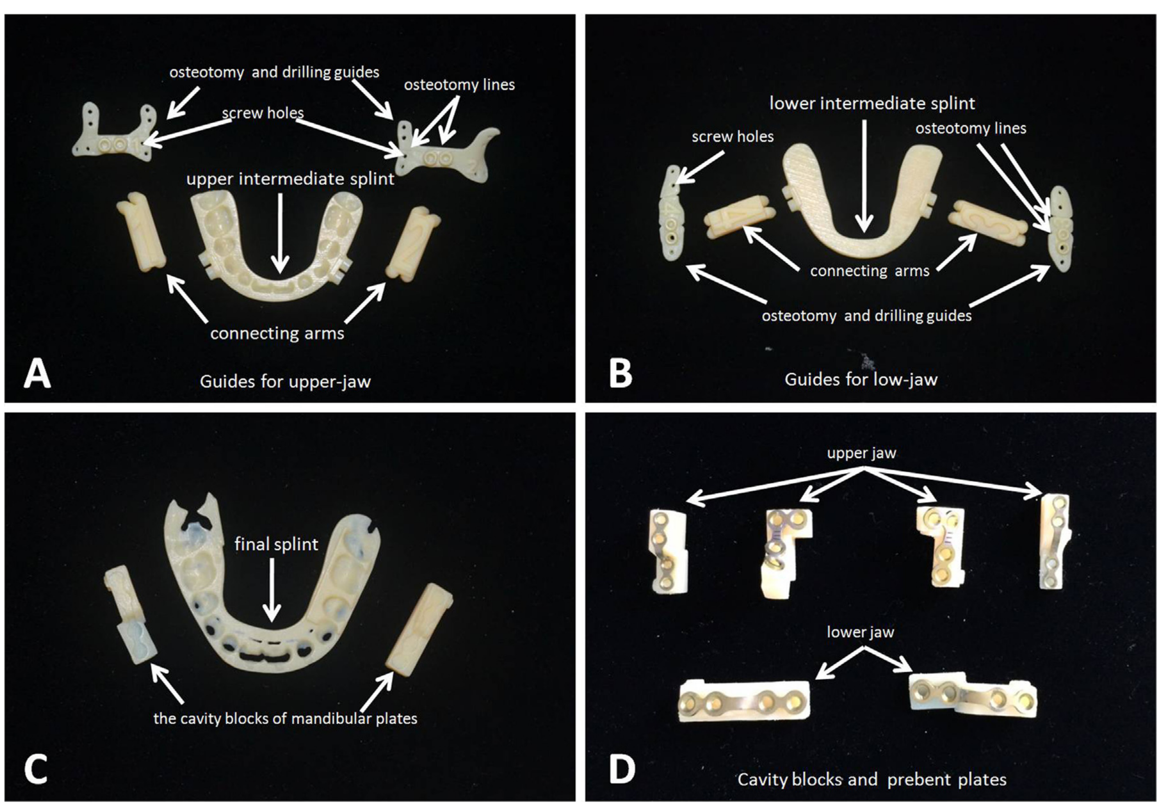

Fig. 2. Navigation system: CAD/CAM osteotomy and drilling guides and the pre-bent titanium plates.

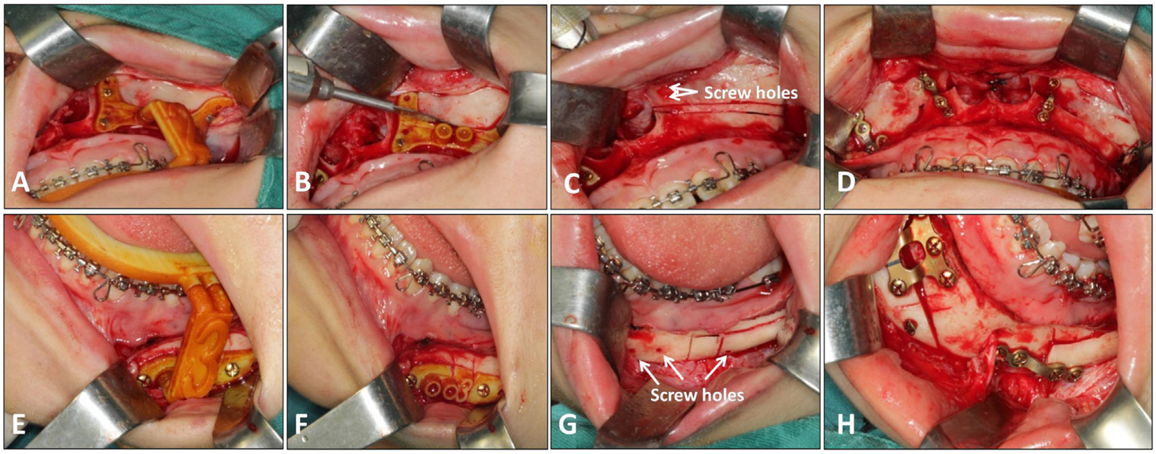

Fig. 3. Application of the navigation system in the operating room. Images A and E show placement, pre-drilling, and fixation of the guides on the bone surfaces. Images B and F show the performance of the osteotomies according to the indication lines on the guides. Images C and G show removal of the osteotomy guides and the redundant bone. Images D and H show the rigid internal fixation with the pre-bent titanium plates.

and pre-drilled holes. As the bone interference was removed and all screws were tightened into the drilled holes, the displaced segments were precisely repositioned to the planned location. During this process, the maxilla was repositioned to the target position without being affected by the mandible. After the BSSRO incision was performed, the mandibular distal segment and the maxilla underwent intermaxillary fixation with the final wafer. The final positions of the mandibular proximal segments were determined by the pre-bent titanium plates and the pre-drilled screw holes. The intermediate wafer was used to help place the guide templates.

After the operation, the patients underwent intermaxillary fixation for approximately 4 weeks.

Cephalometric assessment

Lateral cephalograms (Veraviewepocs 2D; Morita, Suita-shi, Osaka, Japan) were obtained for cephalometric analysis at three time points: pre-surgery (T1), 1 month after surgery (T2), and at least 18 months after surgery (T3). Ten measurements were made to evaluate the skeletal changes after bimaxillary osteotomies of the jaws. The cephalometric parameters at T1, T2, and T3 were examined by analysis of variance (ANOVA) and Student–Newman–Keuls test. All data were analyzed using SPSS version 12.0 (SPSS Inc., Chicago, IL, USA). A P-value of <0.05 was considered significant.

Comparison of the simulated plan and the actual postoperative outcome

Linear and angular measurements of the hard tissues were made. These measurements were made in the virtual simulation and at T2 using the retrieved CT images. The intra-class correlation coefficient was calculated, which can range between 0 (no correlation) and 1 (total correlation).

Deviations between the virtual orthognathic plan models and models constructed from the postoperative CT scans captured at T2 were measured using the 3D Deviation function in Geomagic Studio 12.0 (3D Systems, Rock Hill, SC, USA). The cranial base and zygomatic arch were chosen as markers to overlap the postoperative image with the simulation model. Colour distance maps were then created to measure how much the actual surgery result differed from the virtual plan. The mean deviation distance was determined for each patient and recorded as the mean ± standard deviation (SD).

Results

All patients tolerated the surgery well. The final splints were successfully applied in all patients after RIF, proving a good occlusion. No complications or relapse were observed during follow-up of at least 18 months.

Cephalometric analysis showed that there was a significant difference between T1 and T2 in seven of the 10 parameters; the exceptions were ANB, SNA, and SNB (Table 1). At T3, SN–MP was 40.1 ± 4.50° and FH–

Table 1. Comparison of cephalometric measurements between the different periods.

Measurements	T1	T2	T3
SNA (°)	78.6 ± 9.61	79.4 ± 8.84	80.1 ± 8.74
SNB (°)	82.5 ± 6.53	80.8 ± 8.32	81.3 ± 7.69
ANB (°)	−3.0 ± 5.82	1.7 ± 3.50	1.3 ± 3.45
SN–MP (°)	48.1 ± 4.31	36.7 ± 3.61[a]	40.1 ± 4.50[b]
uOP-SN (°)	12.4 ± 1.95	17.6 ± 1.52[a]	15.5 ± 1.89[b]
ODI (°)	49.4 ± 8.12	73.5 ± 5.26[a]	68.2 ± 6.10
Angle of convexity (°)	−0.1 ± 1.27	2.3 ± 1.84[a]	2.1 ± 2.01
FH–MP (°)	42.9 ± 6.77	34.6 ± 3.72[a]	37.4 ± 3.65[b]
S–Go/N–Me (%)	54.2 ± 5.33	60.6 ± 5.64[a]	58.8 ± 5.12
N–ANS/N–Me (%)	40.7 ± 5.19	46.5 ± 3.49[a]	46.2 ± 4.25

SNA, sella–nasion–A-point; SNB, sella–nasion–B-point; ANB, A-point–nasion–B-point; SN–MP, sella–nasion line to mandibular plane; uOP–SN, upper occlusal plane to sella–nasion plane; ODI, overbite depth indicator; FH–MP, Frankfort horizontal to mandibular plane; S–Go, sella to gonion; N–Me, nasion to menton; N–ANS, nasion to anterior nasal spine; N–Me, nasion to menton.

[a] Significant difference between T1 and T2: $P < 0.05$.

[b] Significant difference between T2 and T3: $P < 0.05$.

Table 2. Comparison of the simulated plan and the actual postoperative outcome through linear and angular measurements of the hard tissues: intra-class correlation coefficient (ICC) and level of significance for each of the measurements in the study.

Measurements	ICC	95% confidence interval	
		Inferior limit	Superior limit
FH–MP (°)	0.84	0.57	0.85
FH–uOP (°)	0.85	0.38	0.96
uOP–MP (°)	0.87	0.77	1.12
N–Bs–A (°)	0.77	0.60	1.23
N–Bs–Me (°)	0.80	0.67	0.95
Bs–Me (mm)	0.84	0.89	1.21

FH–MP, angle formed between the Frankfort plane and the mandibular plane (formed by two points located in the mandibular angles and menton); FH–uOP, angle formed between the Frankfort plane and the occlusal plane (formed by the maximum intercuspation points of the first molars and by a medial point in the incisal occlusal region); uOP–MP, angle formed between the occlusal plane and the mandibular plane; N–Bs–A, nasion–Bs (most anterior point of the foramen magnum)–A-point (most concave point and medial point at the maxilla bone level) angle; N–Bs–Me, nasion–Bs–menton angle; Bs–Me, distance between Bs and menton.

MP was 37.4 ± 3.65°, both showing a statistically significant increase compared with T2 ($P < 0.05$). Mean uOP–SN values were 15.5 ± 1.89° at T3 and 17.6 ± 1.52° at T2, showing a statistically significant decrease ($P < 0.05$). The other parameters showed no statistically significant differences.

A high degree of correlation between the virtual simulation and the CT images at T2 was found for all linear and angular measurements made (Table 2). This was statistically significant ($P < 0.05$) and showed a high degree of correlation between the predicted outcome and the final result for these 3D measurements.

Photographs of the facial profile and occlusion and radiographs were acquired preoperatively and postoperatively for the study patients. The facial profile and occlusion improved significantly and a good therapeutic effect was observed for the open bite deformity (Fig. 4).

The deviations of every bone segment (Table 3) of the 12 patients were obtained using colour map analysis (Fig. 5). The deviations between the preoperative plans and postoperative actual results were evaluated using a threshold value of <2 mm[10]. The frequency of such deviations was used as a measurement of accuracy. According to this definition, the accuracy was over 95% in all bone segments in nine patients (range in all patients, 68–100%; mean ± SD, 95.3 ± 9.79%).

Discussion

In this study, the navigation system using CAD/CAM osteotomy and drilling guides combined with pre-bent titanium plates was applied and investigated in patients treated for a severe skeletal open bite. The major finding of the study was that the navigation system could accurately transfer the virtual plan to the actual operation during the bimaxillary osteotomies of the

Fig. 4. Facial profile, occlusion, and radiographs at the three different time points.

Table 3. Deviations between the virtual plans and actual surgeries[a].

Patient	Sex	Deviation (mm)							
		Maxillary segment	Error <2 mm (%)	Mandibular distal segment	Error <2 mm (%)	Mandibular proximal segment (except the chin)			
						Left	Error <2 mm (%)	Right	Error <2 mm (%)
1	M	0.690 ± 1.130	100	1.311 ± 2.109	98	0.709 ± 1.178	100	0.682 ± 1.104	100
2	M	0.877 ± 1.011	100	1.123 ± 1.881	100	0.647 ± 1.012	100	0.786 ± 0.919	100
3	F	1.109 ± 1.332	99	1.511 ± 1.673	97	1.125 ± 1.432	98	1.162 ± 0.986	100
4	M	0.243 ± 0.453	100	0.763 ± 1.023	100	0.433 ± 1.216	100	0.523 ± 1.324	100
5	F	0.725 ± 1.231	100	1.457 ± 2.123	95	0.899 ± 1.263	100	0.825 ± 1.612	99
6	F	1.342 ± 1.873	96	1.732 ± 2.113	93	1.345 ± 1.932	96	1.573 ± 0.937	98
7	F	0.246 ± 0.536	100	0.563 ± 0.762	100	0.487 ± 0.611	100	0.513 ± 0.701	100
8	M	2.134 ± 2.326	76	2.556 ± 2.852	68	2.145 ± 1.972	78	2.462 ± 1.693	70
9	M	0.352 ± 0.412	100	0.583 ± 0.783	100	0.502 ± 0.893	100	0.490 ± 0.692	100
10	M	0.934 ± 1.264	100	2.109 ± 1.923	71	1.892 ± 1.935	70	2.014 ± 1.873	73
11	F	0.147 ± 0.338	100	0.480 ± 0.821	100	0.298 ± 0.723	100	0.324 ± 0.492	100
12	M	0.479 ± 1.172	100	0.860 ± 1.782	98	0.772 ± 1.253	100	0.689 ± 1.670	100

F, female; M, male.
[a] Data are expressed as mean ± SD, $n = 12$.

jaws, without relapse, in patients with a severe skeletal open bite.

An increasing number of studies have confirmed that 3D virtual reality can accurately simulate and design surgical solutions and has some advantages compared to traditional model surgery. With the CAD/CAM technique, precise simulation of the surgical movements can minimize errors during the fabrication of the model surgical wafers. In prior reports, CAD/CAM techniques have been used to fabricate intermediate surgical wafers to transfer the virtual plan to the operating room[10–13]. Although some errors could be avoided compared to traditional model surgery, they could still not perform vertical control of the maxilla since the unstable mandible determined the position of the maxilla.

A number of methods have been used to overcome the autorotation of the mandible when repositioning the maxilla during bimaxillary osteotomies of the jaws. In one study, CAD/CAM cutting templates and positioning templates made it possible to independently reposition the maxilla[14]. Another study used measurements of internal reference points and external reference points in addition to special instruments, requiring complex instrumentation and with limitations in vector control[15]. These previous methods of CAD/CAM focused mainly on aiding the surgical design and guiding the osteotomy with the help of a computer, and ignored the precise positioning of the titanium plates.

In the present study, the individual implants were used when repositioning the maxilla to achieve precise RIF. Bai et al.[16] described a case series in which they used a CAD/CAM locating guide and manually pre-bent titanium plates on a stereolithographic model. Mazzoni et al.[17] used customized 3D-printed titanium plates to reposition the maxilla in 10 patients; the accuracy was 100% in seven patients. Kwon et al.[18] reported that using conventional articulator splints for maxillary osteotomies resulted in a mean ± SD accuracy of 1.17 ± 0.74 mm. They compared this with the accuracy of surgeries using 3D-printed splints derived from virtual plans and found 3D-printed splints to be more precise with a mean ± SD deviation of 0.95 ± 0.58 mm. Kraeima et al.[19] used patient-specific CAD/CAM templates for Le Fort I osteotomies, resulting in a mean ± SD deviation of 1.3 ± 1.4 mm. No individual implant has been reported to treat skeletal open bite in bimaxillary osteotomies of the jaws.

In some previous studies, a personalized navigation device was designed to locate

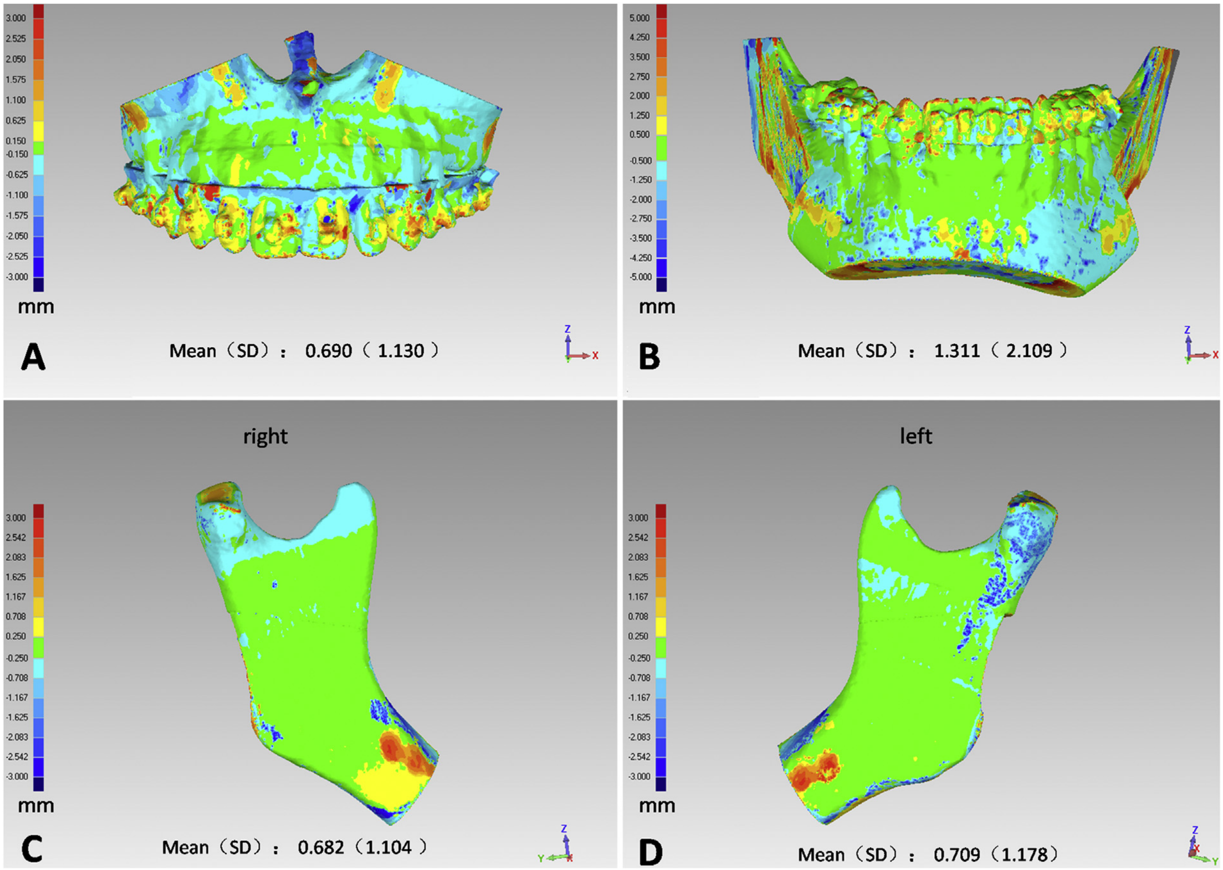

Fig. 5. Comparison of the simulated plan and the actual postoperative outcome using colour distance maps: (A) the maxillary segment; (B) the mandibular distal segment; (C) the right mandibular proximal segment; (D) the left mandibular proximal segment.

the maxilla using the upper part of the Le Fort I osteotomy. This was done to avoid surgical errors caused by an unstable mandible position[20,21]. In the present study, the osteotomy lines indicated by the guiding template facilitated reproduction of the planned Le Fort I osteotomy lines. The pre-drilled screw holes and the pre-bent plates included information concerning the final position of the bone segments after osteotomy. Once the corresponding titanium plates had been placed on the bone surface and the screws had been tightened, the maxilla could be placed precisely in the planned position independent of the condyle or mandible, even if the maxilla had to be moved vertically or tilting of the occlusal plane was necessary. The final positions of the bone segments were determined by the pre-bent titanium plates and the pre-drilled screw holes.

After surgery, a functional occlusion was observed, with normal overbite, overjet, and adequate intercuspation, a class I canine relationship and a class I molar relationship bilaterally, and midlines that nearly coincided. Postoperative cephalometric results showed clockwise rotation of the maxilla and anticlockwise rotation of the mandible, contributing to the improvement in facial profile, and the vertical skeletal dysplasia with open bite was eliminated. A statistically significant difference in SN–MP, uOP–SN, and FH–MP was found between T3 and T2. This indicates that the patients showed a tendency of recurrence after a long period of time. A clockwise rotation of the mandibular plane and anticlockwise rotation of the occlusal plane were performed. However, the trend of relapse was not obvious, while the S–Go/N–Me and N–ANS/N–Me did not show a statistically significant change.

Relapse of an anterior open bite may occur because of various factors, such as tongue size or posture, an unfavourable growth pattern, orofacial musculature, respiratory problems, careless orthodontic preparation, dental movements, and condylar resorption after orthognathic surgery[22]. However, the criteria for assessing the stability and relapse of the correction of an anterior open bite have not been defined quantitatively.

Marchetti et al.[23] performed one of the first comparisons between virtually planned surgery and the postoperative outcome in 25 patients. This comparison was done using a surface-to-surface best fit of the two virtual models. The measures were presented as the mean distance between the geometric models within 2 mm of the planned outcome (surface % <2 mm). The same type of comparison was performed by Mazzoni et al.[24] and Tucker et al.[25]. According to this criterion, the accuracy was over 95% in all bone segments in nine patients in the present study. Only in one case were the deviations of the four segments considered to indicate inaccuracy. Furthermore, the deviations of the mandibular proximal segment and right mandibular distal segment were not accurate in one case. According to prior studies, the success criterion is usually presented as the frequency of deviation <2 mm[10]. With regard to the maxilla segment – the most important segment – 11 cases were considered to be precise.

This study also made use of an additional small technique in the operation. When fixing the titanium plates with screws, the first one should not be tightened before the others have been screwed into the holes. After that, they can gradually be tightened at the same time. In this way, the slight transformation of the titanium plates or bone mass caused by the tightening of the first screw can be avoided.

This will help the navigation system to work more accurately.

Although the final results showed that the navigation system is effective in the treatment of severe skeletal open bite, some problems were also found in the experimental analysis. The height of the posterior maxilla is usually excessive in those with a severe skeletal open bite, while the maxilla usually needs a clockwise rotation when treating this type of patient. The method presented in the Materials and methods section for the partial removal of the maxilla to avoid interference is subjective. As the maxillary bone is elastic, the lack of bone removal in the posterior maxilla may lead the anterior part to a predetermined position, where the increasing height of the posterior part is insufficient. This may lead to postoperative relapse. The application of the navigation system presented in this article together with a mandibular intermediate wafer could represent a better choice for the treatment of a severe skeletal open bite. This dual localization might be able to achieve a better maxillary positioning. This dual positioning guide will be examined and tested for surgery in subsequent studies.

Although the system presented herein achieved an accurate transfer, the increased radiation exposure and cost may represent a non-negligible limitation of this system. Furthermore, accurate soft tissue simulation postoperative is difficult to achieve right now. Problems related to soft tissue simulation still remain to be studied. In addition, errors still occur when manually bending the titanium plates according to the cavity blocks.

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Competing interests

None declared.

Ethical approval

The study protocol was approved by the West China Hospital of Stomatology Ethics Committee (judgement reference number WCHSIRB-ST-2014-137).

Patient consent

Patient consent was obtained to publish the clinical photographs.

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