Accuracy of virtual surgical planning in two-jaw orthognathic surgery: comparison of planned and actual results

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Objective. This study aims to evaluate the accuracy of virtual surgical planning in two-jaw orthognathic surgery via quantitative comparison of preoperative planned and postoperative actual skull models.
Study Design. Thirty consecutive patients who required two-jaw orthognathic surgery were included. A composite skull model was reconstructed by using Digital Imaging and Communications in Medicine (DICOM) data from spiral computed tomography (CT) and STL (stereolithography) data from surface scanning of the dental arch. LeFort I osteotomy of the maxilla and bilateral sagittal split ramus osteotomy (of the mandible were simulated by using Dolphin Imaging 11.7 Premium (Dolphin Imaging and Management Solutions, Chatsworth, CA). Genioplasty was performed, if indicated. The virtual plan was then transferred to the operation room by using three-dimensional (3-D)-printed surgical templates. Linear and angular differences between virtually simulated and postoperative skull models were evaluated.
Results. The virtual surgical planning was successfully transferred to actual surgery with the help of 3-D-printed surgical templates. All patients were satisfied with the postoperative facial profile and occlusion. The overall mean linear difference was 0.81 mm (0.71 mm for the maxilla and 0.91 mm for the mandible); and the overall mean angular difference was 0.95 degrees.
Conclusions. Virtual surgical planning and 3-D-printed surgical templates facilitated the diagnosis, treatment planning, and accurate repositioning of bony segments in two-jaw orthognathic surgery. (Oral Surg Oral Med Oral Pathol Oral Radiol 2016; 122:143-151)

Two-jaw orthognathic surgery, LeFort I osteotomy of the upper jaw, combined with sagittal split ramus osteotomy (SSRO) or intraoral vertical ramus osteotomy (IVRO) of the lower jaw, is an efficient procedure to correct severe dentomaxillofacial deformities.[1,2] The success of two-jaw surgery relies on surgical technique and accurate surgical planning.[3,4] Conventional treatment planning for two-jaw surgery involves diagnosis with two-dimensional (2-D) cephalometric radiography, face-bow transfer and model surgery on plaster dental cast, and fabrication of intermediate and final occlusal splint. This conventional process is generally satisfactory but has a number of limitations, such as time-consuming process, complexity, even inaccuracy.[5-8]

Virtual surgical planning and rapid prototyping (RP) technology offers new possibilities to obtain a comprehensive three-dimensional (3-D) evaluation of the dental arches and the surrounding skeletal structures to simulate different surgical plans and predict the corresponding results, as well as to facilitate the transfer of the virtual surgical plan to actual outcome using 3-D−printed splints and guiding templates.[9,10] Numerous reports on virtual surgical planning have been published, and most are case reports to investigate feasibility or to emphasize the potential advantages of virtual surgical planning over conventional methods.[11-13] However, investigation on the accuracy of the virtual surgical planning in two-jaw orthognathic surgery in a series of patients has been limited.

The purpose of this study was to evaluate the degree to which surgical outcomes in two-jaw orthognathic surgery, using virtual surgical planning and 3-D−printed surgical templates, correlate with the virtually simulated outcomes in a series of 30 patients.

MATERIALS AND METHODS

Patients

Thirty consecutive patients who required two-jaw orthognathic surgery at the West China Hospital of Stomatology, at Sichuan University (Chengdu, China),

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Statement of Clinical Relevance

Virtual surgical planning and three-dimensional printed surgical templates facilitated the diagnosis, treatment planning, and accurate bony segments repositioning in two-jaw orthognathic surgery.

between September 1, 2014, and August 31, 2015, were included in this study. The study protocol was approved by the West China Hospital of Stomatology Institutional Review Board, and all of the participants signed informed consent agreements. Each patient accepted LeFort I osteotomy of the maxilla combined with bilateral SSRO of the mandible, and genioplasty was performed, if indicated (Table I). Patient 4 in Table I was chosen as a representative case to illustrate the procedures discussed below.

Virtual surgical planning

High-resolution spiral computed tomography (CT) and surface scanning of the dental arch (3 shape, Copenhagen, Denmark) for each patient were performed before and 1 month after surgery (just before postoperative orthodontic treatment). DICOM data from CT and STL data from dental arch scanning were superimposed to construct a composite skull model with accurate dentition. After a comprehensive 3-D evaluation, virtual surgical planning and simulation were performed by using Dolphin Imaging 11.7 Premium (Dolphin Imaging and Management Solutions, Chatsworth, CA) and Mimics software (version 10.01; Materialise, Leuven, Belgium) (Figure 1). A series of surgical templates were fabricated by using RP technology to help the transfer of the virtual plan to actual surgery (Figure 2).

Transfer of the virtual plan during surgery using 3-D-printed templates

The transfer of the virtual plan into the operative environment relied on a series of surgical templates, including a final occlusal splint, two pairs of 3-D arms, and a pair of bone attachments with indication of osteotomy line (Figure 3A). Before osteotomy of the upper jaw, the final occlusal splint and the first pair of 3-D arms were used to determine the position of the bone attachments (Figure 3B). Then, bone attachments with guiding lines were fixed on the surface of the maxilla with mini-screws, and the splint and arms were removed (Figure 3C). After down-fracture of the maxilla (Figure 3D), the final occlusal splint, the second pair of 3-D arms, and the bone attachments were connected to each other to directly reposition the maxilla in the virtually simulated position independent of the mandible (Figure 3E). After repositioning and fixation of the maxilla, bilateral SSRO of the mandible was performed, and a normal occlusion was achieved with the help of the final occlusion splint alone (Figure 3F).

Quantitative analysis of the accuracy of virtual surgical planning

To evaluate the accuracy of virtual surgical planning in two-jaw orthognathic surgery, symmetry planes and landmarks on the surface of the skull were defined. Frankfort horizontal plane (FHP), midfacial plane (perpendicular to the FHP through the nasion), and coronal plane (perpendicular to the FHP through the sella point) were the three selected symmetry planes. Midpoint of the contact of the maxillary and mandibular central incisors (UI, LI), and the mesiobuccal cusp of the first maxillary and mandibular molars (U6, L6) were the six chosen volumetric landmarks (Figure 4). For linear analysis, the distance between the selected landmarks and the symmetry planes was measured, and the difference between simulated and postoperative models was calculated; for angular analysis, values of the angles constructed by the occlusal, palatal, and mandibular planes to the FHP and the midfacial plane, respectively, were determined on simulated and postoperative models, and the difference between the two models was calculated.

Table I. Information of all patients included in this study and the surgeries they accepted

Patient (No.)	*Gender*	*Age (Years)*	*Dentofacial deformity*	*Surgical treatment*
1	M	20	CIII, RU, PL	I + II
2	M	22	CIII, RU, PL	I + II
3	F	22	CIII, RU, PL, FA	I + II + III
4	F	22	CIII, RU, PL, VEU, AOB	I + II
5	F	21	CIII, RU, PL, FA	I + II + III
6	F	20	CIII, RU, PL	I + II + III
7	M	19	CIII, RU, PL, FA	I + II
8	F	21	CIII, RU, PL	I + II + III
9	M	23	CIII, RU, PL, FA	I + II + III
10	M	22	CIII, RU, PL	I + II + III
11	M	19	CIII, RU, PL	I + II
12	F	19	CIII, RU, PL, FA, AOB	I + II + III
13	F	24	CIII, RU, PL	I + II + III
14	M	29	CIII, RU, PL	I + II
15	F	30	CII, PU, RL, VEU	I + II + III
16	M	22	CIII, RU, PL	I + II + III
17	M	25	CIII, RU, PL, FA	I + II
18	M	27	CIII, RU, PL	I + II
19	F	19	CIII, RU, PL, FA	I + II + III
20	M	20	CIII, RU, PL	I + II + III
21	F	19	CIII, RU, PL, FA	I + II + III
22	F	19	CIII, RU, PL	I + II
23	M	21	CIII, RU, PL	I + II
24	F	20	CII, PU, RL, AOB	I + II + III
25	F	19	CII, PU, RL	I + II + III
26	M	25	CIII, RU, PL, FA	I + II
27	M	22	CIII, RU, PL, FA	I + II + III
28	M	23	CIII, RU, PL	I + II
29	M	21	CIII, RU, PL, VEU	I + II
30	F	20	CIII, RU, PL, FA	I + II + III

CIII, class III malocclusion; *CII*, class II malocclusion; *RU*, retrognathia of upper jaw; *RL*, retrognathia of lower jaw; *PU*, prognathia of upper jaw; *PL*, prognathia of lower jaw; *VEU*, vertical excess of upper jaw; *FA*, facial asymmetry; *AOB*, anterior open bite; *I*, LeFort I osteotomy of maxilla; *II*, bilateral sagittal split ramus osteotomy (SSRO) of mandible; *III*, genioplasty.

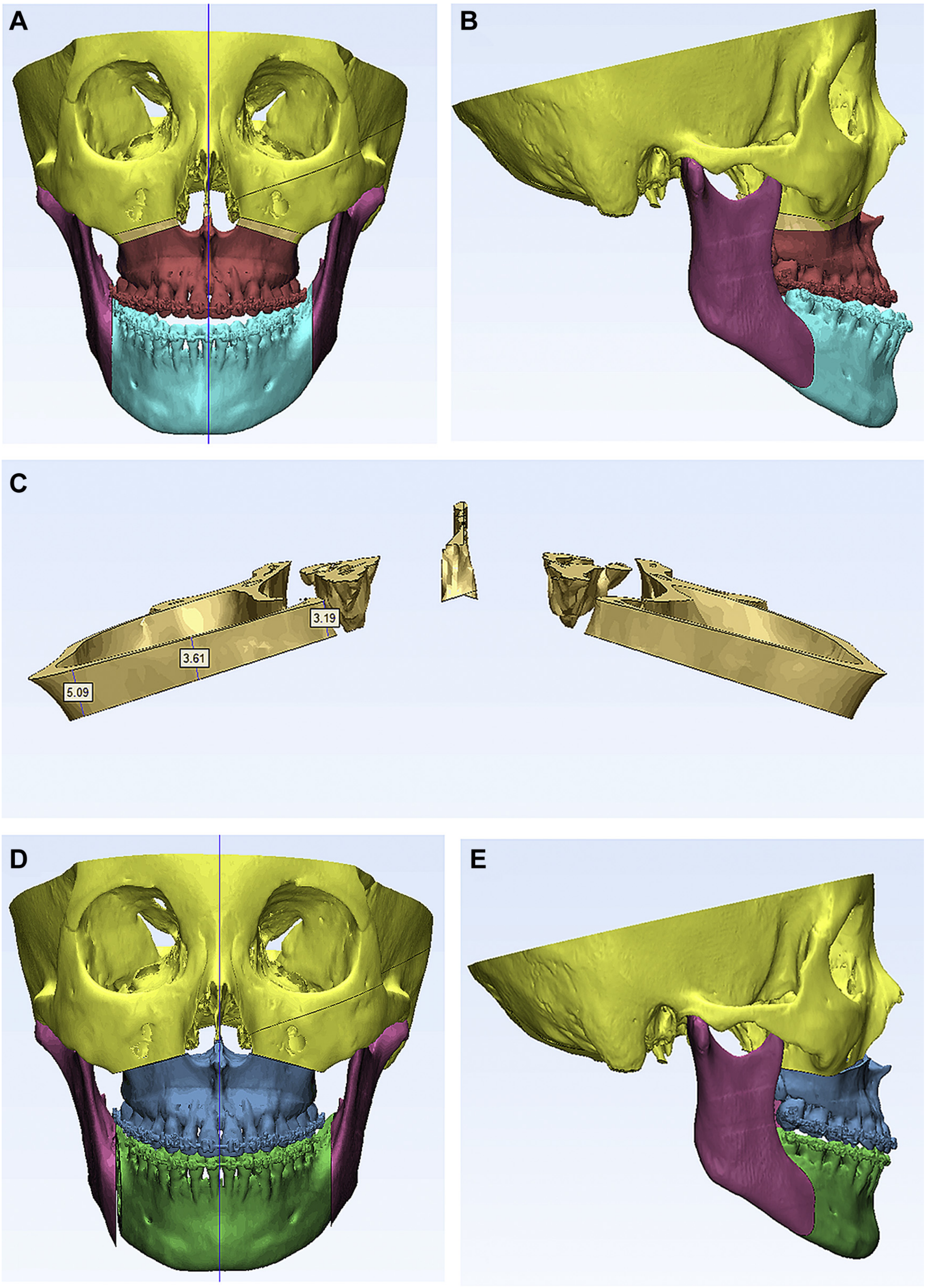

Fig. 1. Scheme showing the process of virtual surgical planning (patient 4 in Table I). The upper jaw was compacted (**A**-**C**) via LeFort I osteotomy, and the final occlusion was achieved after setback of the mandible by bilateral sagittal split ramus osteotomy (D, E).

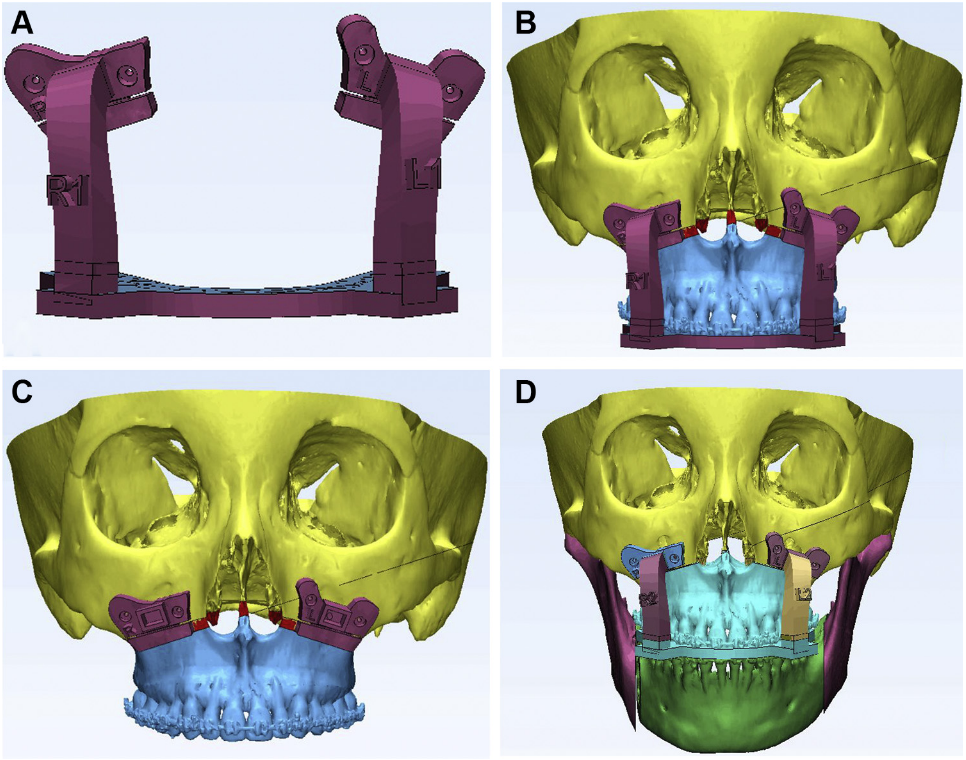

Fig. 2. **A**, A series of surgical templates were designed to help the transfer of the virtual plan to actual surgery. **B** and **C**, Bone attachments were fixed on the surface of maxilla using mini-screws with the support of the occlusion plate and the first pair of three-dimensional (3-D) arms. **D**, The new 3-D position of the maxilla was determined by the occlusion splint and a second pair of 3-D arms, and the final occlusion was determined by the same occlusion splint.

Statistical analysis

All data were analyzed by using SPSS 12.0 (SPSS Inc., Chicago, IL). Paired *t* test was used to calculate the difference between the virtually planned position and the actual position of the jaws and teeth. Statistical significance was set at $P < .05$.

RESULTS

General outcomes

The virtual surgical planning was successfully transferred to actual surgery on all patients with the help of a series of 3-D−printed surgical templates, consisting of a final occlusal splint, two pairs of 3-D arms, and a pair of bone attachments. All patients were satisfied with the final results, including facial profile and occlusion. Patient 4 in Table I, a 22-year-old female diagnosed with skeletal III malocclusion and open bite, was chosen as a representative case to illustrate the changes in the facial profile, occlusion, and radiographs (Figures 5-7). Maxillary advancement and impaction after LeFort I osteotomy and mandibular setback by bilateral SSRO were performed on this patient. The swelling of soft tissue was still somewhat noticeable 1 month after surgery, but the facial profile and occlusion were satisfactory.

Quantitative analysis

The linear difference between the virtually simulated model and the actual postoperative model is presented in Table II. The overall mean linear difference (mean difference of the distance between UI, LI, U6, and L6 to the FHP and the midfacial and coronal planes) was 0.81 mm, the mean linear difference for maxillary landmarks (mean difference of the distance between UI, U6 to the FHP and the midfacial and coronal planes) was 0.71 mm, the mean linear difference for mandibular landmarks (mean difference of the distance between LI, L6 to the FHP and the midfacial and coronal planes) was 0.91 mm; the overall mean linear difference for both maxillary and mandibular landmarks relative to FHP was 0.92 mm; the mean linear difference relative to the midfacial plane was 0.55 mm; and the mean linear difference relative to the coronal plane was 0.97 mm. Thus, it seems that virtual planning worked better on the maxilla than on the mandible (0.71 mm vs 0.91 mm) and showed better control for the deviation from the midfacial plane (0.55 mm) than the FHP (0.92 mm) and the coronal plane (0.97 mm). The angular difference between the virtually simulated and the actual postoperative models is presented in Table III. The

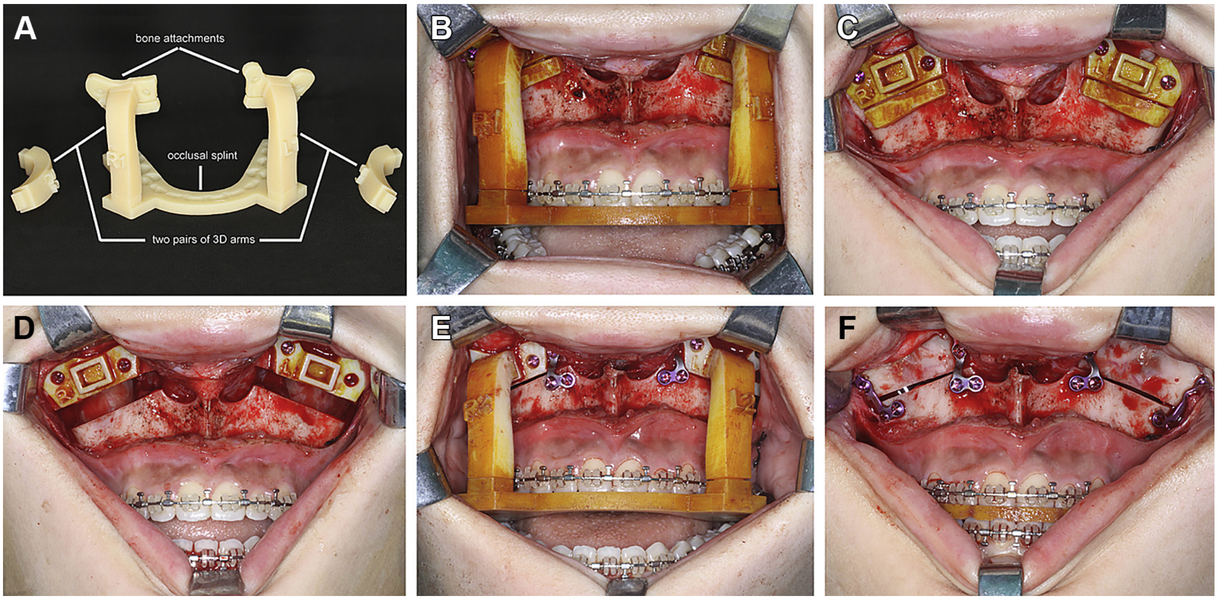

Fig. 3. A series of surgical templates were fabricated by rapid prototyping technology to support the intraoperative translation of the virtual plan to actual surgery. **A**, The surgical templates consisted of three parts: an occlusion splint, two pairs of 3-D arms, and a pair of bone attachments. **B** and **C**, Bone attachments were fixed on the surface of the maxilla by using mini-screws with the support of the occlusion plate and the first pair of 3-D arms. **D**, LeFort I osteotomy and impaction of the upper jaw were then performed, according to the indication line of the bone attachments. **E**, The same occlusion splint and a second pair of 3-D arms were used to determine the new 3-D position of the maxilla. **F**, Subsequently, bilateral sagittal split ramus osteotomy of the mandible was performed, and the final occlusion was determined by the same occlusion splint.

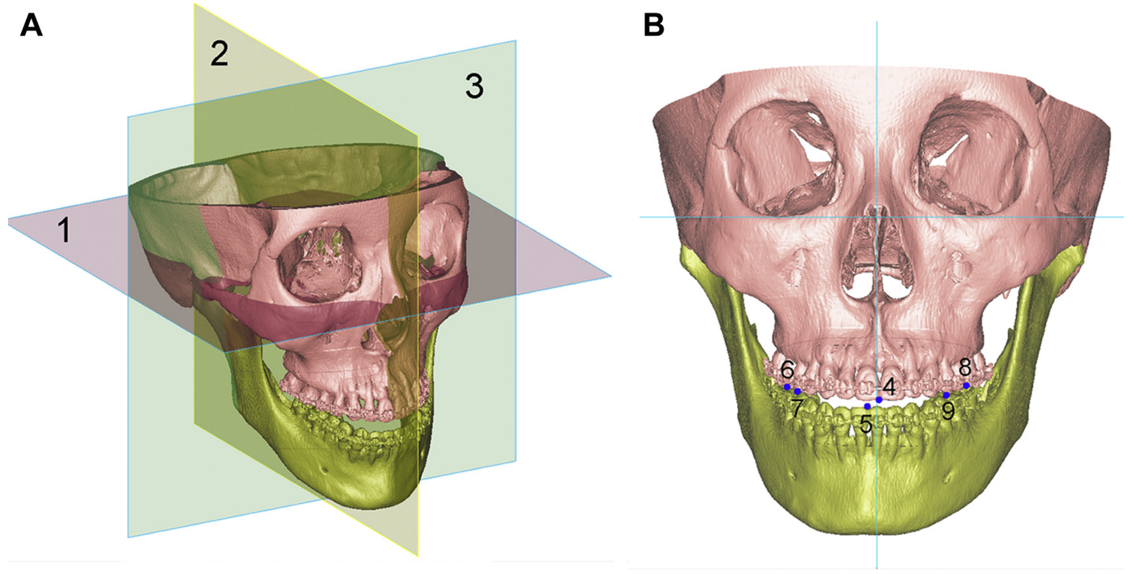

Fig. 4. Symmetry planes and landmarks on the surface of the skull. **A**, 1 = Frankfort horizontal plane (FHP); 2 = midfacial plane (perpendicular to the FHP through the nasion); 3 = coronal plane (perpendicular to the FHP through the sella point). **B**, 4 = Midpoint of the contact of the maxillary central incisors; 5 = midpoint of the contact of the mandibular central incisors; 6 and 8 = mesiobuccal cusp of the first maxillary molars; 7 and 8 = mesiobuccal cusp of the first mandibular molars.

overall mean angular difference was 0.95 degrees, the mean angular difference relative to FHP was 1.1 degrees, and the mean angular difference relative to midfacial plane was 0.83 degrees.

DISCUSSION

There have been numerous publications on virtual surgical planning in orthognathic surgery,[14-16] most reporting one or several cases to emphasize the

Fig. 5. Facial profile of the representative patient (#4 in Table I) before and after surgery.

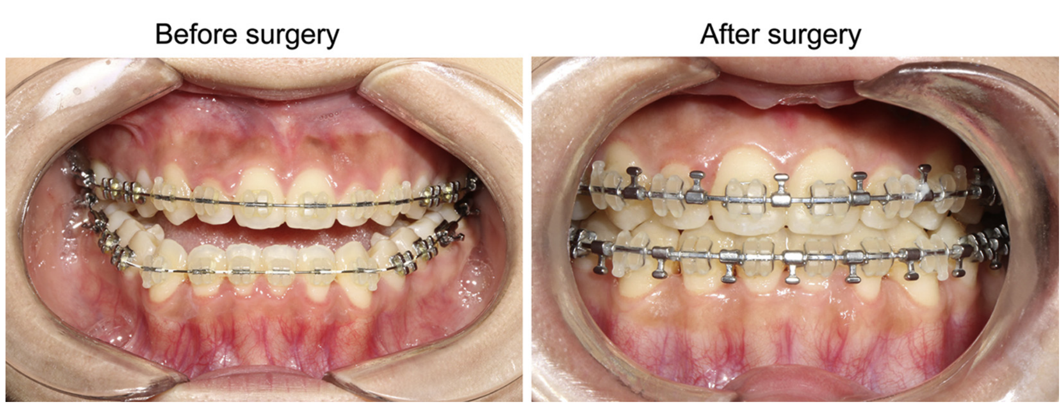

Fig. 6. Final occlusion of the representative patient (#4 in Table I) before and after surgery.

hands-on planning. Because of the differences in the presentation of data, it was almost impossible to perform a meta-analysis.[17] This preliminary study investigated the accuracy of virtual surgical planning in two-jaw orthognathic surgery by comparing linear and angular differences between planned and actual results in 30 patients. The new 3-D position of the maxilla was determined independent of that of the mandible by using a series of 3-D-printed surgical templates; thus, the process of dental cast preparation, face-bow transfer to articulator, model surgery, and intermediate splint were not needed. Lin et al.[18]

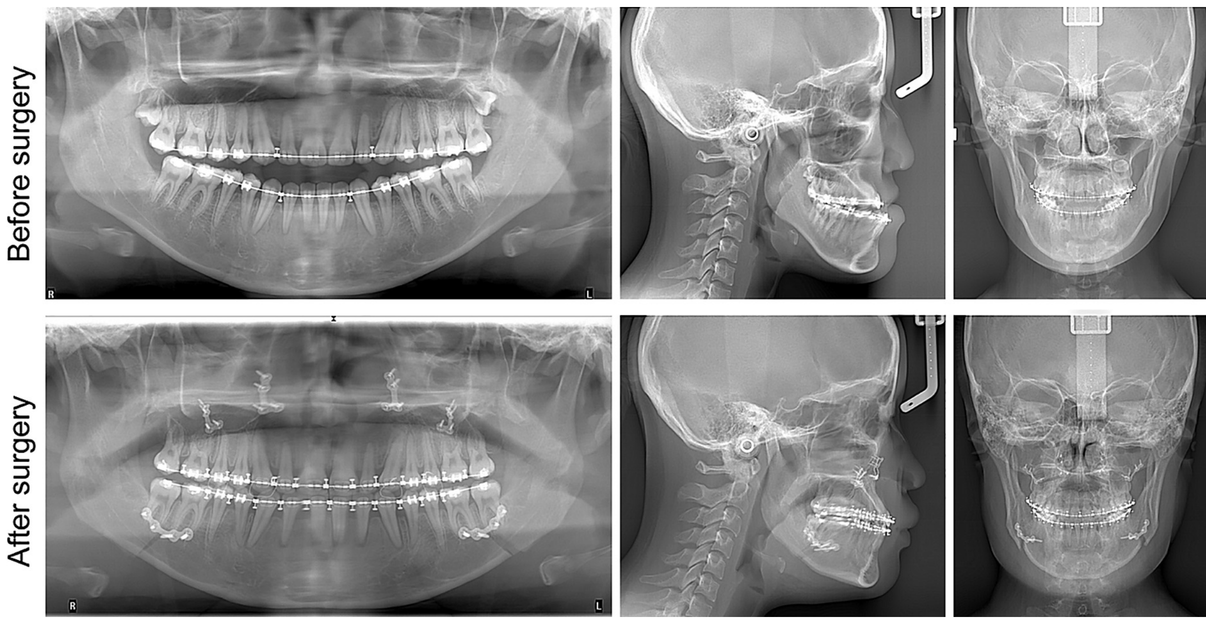

Fig. 7. Panoramic and cephalometric images of the representative patient (#4 in Table I) before and after surgery.

Table II. Quantitative results of linear differences (mm) between the virtually simulated and actual postoperative models

Landmarks	*Difference of the distance to FHP*	*Difference of the distance to midfacial plane*	*Difference of the distance to coronal plane*
UI	0.7 ± 0.3	0.4 ± 0.1	0.8 ± 0.4
LI	1.1 ± 0.5	0.5 ± 0.3	1.0 ± 0.4
U6 (R)	0.8 ± 0.4	0.6 ± 0.2	0.9 ± 0.3
U6 (L)	0.7 ± 0.3	0.5 ± 0.2	1.0 ± 0.5
L6 (R)	1.0 ± 0.4	0.7 ± 0.3	1.1 ± 0.6
L6 (L)	1.2 ± 0.5	0.6 ± 0.3	1.0 ± 0.5

FHP, frankfort horizontal plane.
Data were expressed as mean ± standard deviation. Thirty patients were included. Paired *t* test was performed, and no significant difference was found.

Table III. Quantitative comparison of angular differences (degrees) between the virtually simulated and actual postoperative models

Symmetry planes	*Angular difference relative to FHP*	*Angular difference relative to midfacial plane*
Occlusal plane	1.1 ± 0.6	0.9 ± 0.4
Palatal plane	0.8 ± 0.3	0.6 ± 0.2
Mandibular plane	1.3 ± 0.6	1.0 ± 0.6

FHP, frankfort horizontal plane.
Data were expressed as mean ± standard deviation. Thirty patients were included. Paired *t* test was performed, and no significant difference was found.

reviewed the reports published in the past 10 years on the use of computer-assisted techniques in orthognathic surgery, including surgical planning, simulation, intraoperative translation of virtual surgery, and postoperative evaluation. It was concluded that use of the computer-assisted technique in orthognathic surgery provides the benefit of optimal functional and aesthetic results, patient satisfaction, precise translation of the treatment plan, and facilitating intraoperative manipulation.[18]

Different methods of presentation of data on comparison of planned and actual skull models following two-jaw orthognathic surgery were reported, such as intraclass correlation coefficient, difference of 3-D surface area, and linear and angular differences in three dimensions.[19-22] In the present study, linear and angular differences between planned and actual results were analyzed. Success criteria were set as 2 mm for the linear difference, and 4 degrees for the angular difference in most publications.[23,24] In this study, results from 30 patients showed that the overall mean linear difference was 0.81 mm, and the overall mean angular difference was 0.95 degrees. In fact, the accuracy of virtual surgical planning had improved compared with our previous study, as a result of surgical experience, 3-D printing technology, and improvement of the elasticity modulus of 3-D-printed surgical templates.[25] It was also found that virtual planning and 3-D-printed surgical templates worked better on the maxilla than on the mandible (0.71 mm vs 0.91 mm for mean linear difference) and showed better control for the deviation from the midfacial plane (0.55 mm) than the FHP (0.92 mm) and the coronal plane (0.97 mm).

Although virtual surgical planning has been widely reported, different methods were applied for the intraoperative translation of the treatment plan. Mazzoni et al. developed a computer-aided design and computer-aided manufacturing (CAD/CAM) technique that enabled fabrication of surgical cutting guides and titanium fixation plates and would allow the upper maxilla to be repositioned correctly without a surgical splint in orthognathic patients, and the accuracy was reported to be 100% in seven out of 10 patients.[26] Kim et al.[27] developed an integrated orthognathic surgery system with 3-D virtual planning and image-guided transfer. During virtual planning, the displacement of the reference points was confirmed by the displacement from conventional paper surgery at each procedure. The results of virtual surgery were transferred to the physical cast models directly through image guidance. The root mean square difference between virtual surgery and conventional model surgery was 0.75 ± 0.51 mm for 12 patients. The root mean square difference between virtual surgery and image-guidance results was 0.78 ± 0.52 mm.[27] Zinser et al.[14] used a surgical splint to determine the position of the maxilla independent of that of the mandible, which was a similar method to the present study. Linear and angular differences in eight patients were evaluated, and it was found that the mean linear differences was less than 1 mm, and the mean angular difference was less than 1 degree in all planes evaluated.[14] Different methods transferring virtual plan to actual surgery may influence the accuracy of the final actual outcomes, so further investigation on the advantages and disadvantages of different intraoperative translation methods are still needed.

CONCLUSIONS

Virtual surgical planning and 3-D-printed surgical templates facilitated the diagnosis, treatment planning, and accurate repositioning of bony segments in two-jaw orthognathic surgery. The linear and angular difference between the virtually simulated and postoperative skull models was clinically acceptable. Results from the 30 study patients showed that the overall mean linear difference was 0.81 mm and that the overall mean angular difference was 0.95 degrees.

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