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Virtual 3D planning and prediction accuracy in two bimaxillary face transplantations in Helsinki

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3D planning;
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Summary *Background:* The aim of this study was to describe the 3D planning process used in our two composite face transplantations and to analyze the accuracy of a virtual transplantation in predicting the end-result of face transplantation.
Methods: The study material consists of two bimaxillary composite face transplantations performed in the Helsinki University Hospital in 2016 and 2018. Computed tomography (CT) scans of the recipient and donor were used to define the osteotomy lines and perform the virtual face transplantation and to 3D print customized osteotomy guides for recipient and donor. Differences between cephalometric linear and angular measurements of the virtually simulated and the actual postoperative face transplantation were calculated.
Results: No changes to the planned osteotomy lines were needed during surgery. The differences in skeletal linear and angular measurements of the virtually simulated predictions and the actual postoperative face transplantations of the two patients varied between 0.1–5.6 mm and 0.7°–4°. The postoperative skeletal relationship between maxilla and mandible in both patients were almost identical in comparison to the predictions.

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Conclusions: 3D planning is feasible and provides close to accurate bone reconstruction in face transplantation. Preoperative virtual transplantation assists planning and improves the outcome in bimaxillary face transplantation.

Introduction

After the first face transplantation (FT) in France in 2005[1], to date at least 45 FTs have been performed worldwide[2]. At least 15 of these have contained varying amounts of facial bone, including the two bimaxillary FTs carried out in Helsinki[3,4]. Inclusion of parts of the facial skeleton presents an extra level of complexity to the technical aspects of facial allograft harvest and inset. Accurate bony reconstruction is critical to the success of transplantation as any size or shape mismatch between the donor and the recipient can affect the alignment, fixation and consolidation of the transplanted bones and hence functional outcomes related to occlusion. Furthermore, osteomyocutaneous facial allografts introduce additional unique challenges related to bone healing and maintenance of bone stock over time[5].

3D planning and CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) technology are widely used in orthognathic and maxillofacial surgery in planning surgery and enabling the manufacturing of customized implants for precise adaptation, reduced surgical times and better cosmesis[6]. Virtual planning in FT has been earlier described in three reports using cadaver models[7-9]. Use of virtual planning and customized cutting guides in FT patients have been previously described by the Baltimore and Ghent teams[10,11].

Since 2016, two composite FTs have been performed in the Helsinki University Hospital. In both cases, thorough 3D planning was used, and customized osteotomy guides were implemented in both the patient and the donor. The aim of this study is to describe the 3D planning process in our two composite FTs and to analyze the accuracy of virtual transplantation in predicting the end-result of transplantation.

Patients and methods

This study was approved by the Helsinki University Hospital ethical committee. The study material consists of two bimaxillary composite FTs performed in the Helsinki University Hospital in 2016 and 2018. Data was collected by reviewing the patient charts for clinical data and CT-scan information for evaluating the skeletal parts of the transplants. The establishment of the Helsinki VCA-team has been published previously[3]. Both patients have given their written consent for publication of their data.

Patients

Both patients had major soft tissue and bony defects of the central face and maxilla and mandible after ballistic injury. Patient 1 had a severe central facial deformity involving maxilla and mandible including loss of facial height. He had severe symptoms related to nasal breathing, eating, speech, and recurrent soft tissue infections. Patient 2 had a severe full facial deformity also with involvement of maxilla and mandible. He had a permanent tracheostomy and problems with lip competence, eating, speech, and left eye dryness due to insufficient lid closure.

3D planning

The 3D planning of the FT operation was performed using Planmeca Romexis® (Planmeca Oy, Helsinki, Finland) and 3D-Systems Geomagic Freeform (3D-Systems, Rock Hill, South Carolina, USA) software. Patient-specific osteotomy guides for both recipient and donor were 3D-printed from an appropriate medically approved plastic.

Planning for the patient revision osteotomy and unknown donor bimaxillary osteotomy

The nasion was the starting point for the 3D planning as this was the first place in the midface with still intact bone. In both patients, the lower orbital margins were damaged and asymmetrical and therefore couldn't be used as a reference level to a normal skeleton. The revision osteotomies were planned to follow approximately the principles of Le Fort II osteotomy lines. In addition, sagittal osteotomy lines were planned from mandibular angle to angle in order to remove the damaged central segment of bone. After defining the osteotomy lines, patient specific osteotomy guides were planned and 3D-printed.

As the shape and size of the donor jaws is unknown before transplantation, generic osteotomy guides for an unknown donor were planned. The osteotomy lines copied from the patient were applied to several randomly selected donor-candidate maxillae and mandibles and virtual bimaxillary transplantations were performed to evaluate the fit with different shaped facial skeletons. Several attempts were made and finally the patient osteotomy lines for midfacial bones were simplified to create an inward cone-shaped area on the midfacial bones.

For the mandible, a challenge was posed by the shortness and medial rotation of the patients' lateral mandible segments. Therefore, the osteotomy lines were created to enable maximum length of the patient's remaining lateral mandibular segments and donor's central mandibular segment. In addition, it was planned to laterally rotate the patient's lateral mandibular segments into a more normal position. The donor planning was conducted using several ran-

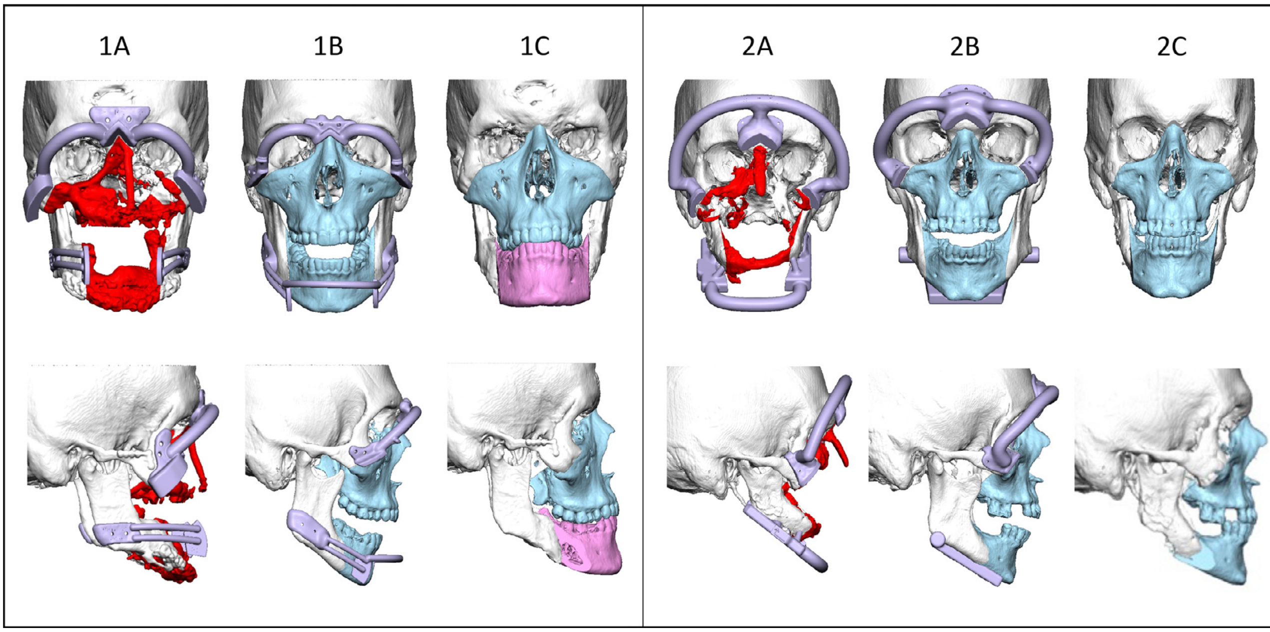

Fig. 1 Real virtual face transplantation (data retrieved from the CT scans of the actual donors).
1A: Patient 1 with the osteotomy guides.
1B: Donor 1 with the osteotomy guides.
1C: Virtual transplantation, patient 1 (mandible not planned preoperatively, marked pink).
2A: Patient 2 with the osteotomy guides.
2B: Donor 2 with the osteotomy guides. 2C: Virtual transplantation, patient 2.

domly selected patient CT scans, that had been obtained for other reasons. Accordingly, generic donor osteotomy guides were planned and printed in case there would be insufficient time to print *in situ* donor-specific osteotomy guides.

Real in situ virtual FT and prediction of the result

At the time of real FT, when the donor was confirmed, an immediate CT-scan of the donor facial skeleton was taken, and the CT-data was sent to Planmeca Oy for immediate 3D-planning. The osteotomy lines were defined, and a virtual FT was performed to verify the fit of the donor skeleton into the patient's face. This also gave us the prediction of the outcome. After designing osteotomies, the donor-specific osteotomy guides were planned and 3D-printed (Figure 1).

Cephalometric analyses

To evaluate the accuracy of the 3D-virtual planning, the 3D CT images of the preoperative prediction of the FT and the actual immediate postoperative FT result were superimposed onto the Sella–Nasion (SN) plane.

The skeletal surgical changes of the maxilla and mandible were assessed using cephalometric landmarks A and B. The linear distances of landmarks A and B between the prediction and the transplant were calculated both horizontally and vertically. The antero-posterior skeletal relationship of the maxilla and mandible in relation to cranial base and to each other were assessed using the angles SNA, SNB, and ANB. Skeletal facial symmetry was assessed by vertical lines drawn perpendicular to the skeletal midpoints of the upper (UI) and lower (LI) central incisors. The cephalometric landmarks were planned so that these anatomical structures would remain unchanged during surgery. The same 3D planning programs were used in the cephalometric analyses and in the planning of the FT.

Results

3D-planning and osteotomy guide production

For both FT patients, we obtained facial skeleton CT data from the donor prior to the transplantation surgery. The data were sent to Planmeca Oy immediately once the suitability of the donor was confirmed. From the time of the donor CT scan it took 8 h in both transplant cases for the planning and delivery of 3D-printed osteotomy guides to the operation theatre. No changes to the planned osteotomy lines were needed and the manufacturing of the guides proceeded exactly as planned beforehand.

Surgery

For both donor facial harvests, the donor-specific osteotomy guides were applied to the planned positions and secured with screws. The maxilla was cut *in situ* according to the osteotomy guides whereas the mandible was first cut *in situ* horizontally at the ramus level and later with the osteotomy guides on the back table. For the second patient, the proximal inferior alveolar nerve was first freed and safeguarded from the line of osteotomy for later neural coaptation. The

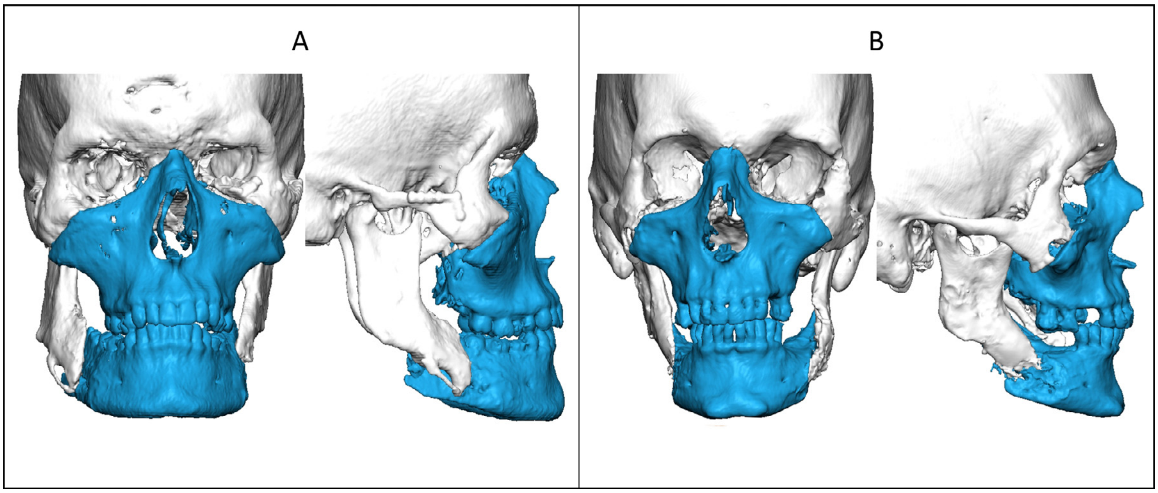

Fig. 2 Immediate result.
A: Patient 1. Immediate result 6 weeks post transplantation.
B: Patient 2. Immediate result 6 days post transplantation.

recipient patients' debridement was performed using the osteotomy guides as planned previously.

For the first patient, the inset of the transplanted bones was performed as planned and took less than 30 min. However, to allow for some margin of error, the donor maxilla was planned to be 2 mm wider and this additional bone was not removed at the time of inset. For the second patient, during the transplant surgery, it was noted that the bone of the patient's left zygomatic arch was not stable as had been predicted. The inset of the maxilla was thus more difficult as the left orbital rim had migrated from its originally planned position. Therefore, additional drilling of the donor nasal bone had to be performed. In both cases, additional recipient patient pterygoid plate and posterior maxilla removal was needed before the donor maxilla would fit as planned. The osteotomies were secured using three Synthes AO Midface 0.8 mm and two Mandible reconstructive 2.0 mm plates.

The first postoperative facial CT scan was taken at 6 weeks for the first and at 6 days postoperatively for the second FT patient (Figure 2).

The accuracy of the prediction compared to the actual result

For the first patient, the maxilla was positioned slightly too caudal due to the excess donor maxillary bone that was planned but not removed during the surgery. For the second patient, the adjustment of the donor and patient radix had resulted in slight malposition and rotation of the donor maxilla (Figure 3).

For both patients, the osteotomy lines for the donor mandible were designed to be as long as possible in the sagittal plane and to include molar teeth. This resulted in a slightly too wide inset of the transplanted bone. Thus, in both patients the inwardly rotated lateral mandibular segments had to be rotated laterally creating some tension in the temporo-mandibular joints. However, for both patients, the position of the transplanted mandibular segment was close to what was planned (Figure 3).

Cephalometric analyses and occlusion

Patient 1: The maxilla (point A) and mandible (point B) of the transplant were advanced horizontally a little less than predicted (3 mm and 5 mm, respectively). Vertically points A and B of the transplant moved downwards (5.2 mm and 5.6 mm). However, the relationship between the maxilla and mandible (angle ANB) was almost identical (2.9°) when compared to the donor (2.0°) and prediction (2.2°). There was a rotation of the transplant to left side (UI 5 mm and LI 2.1 mm). Postoperative overjet was 4 mm and overbite 1 mm. The donor had a full dentition with persisting lower deciduous second molars. During the transplantation, in order to fit the donor mandible segment, the TMJ joints were forced to rotate laterally. This created tension which resulted in postoperative rotation of the mandible and Angle class II occlusion in the early postoperative analysis. However, the occlusion settled during the recovery and Angle class I occlusion was achieved without surgery. (Table 1, Figure 4)

Patient 2: Points A and B of the transplant were advanced horizontally slightly more than predicted (4 mm and 5.4 mm, respectively). There was a minor movement upwards (0.1 mm and 1.6 mm). The relationship between the maxilla and mandible (angle ANB) was almost the same (5°) as in the donor (5.1°) and prediction (4°). The preexisting skeletal mild class II remained the same. A rotation of the transplant to the left (UI 0.1 mm and LI 2.3 mm) was due to left zygomatic fail. The postoperative overjet was 3 mm and overbite 1 mm. The donor had several missing permanent teeth including all lower permanent molars. Despite this, the occlusion was stable postoperatively. (Table 1, Figure 4).

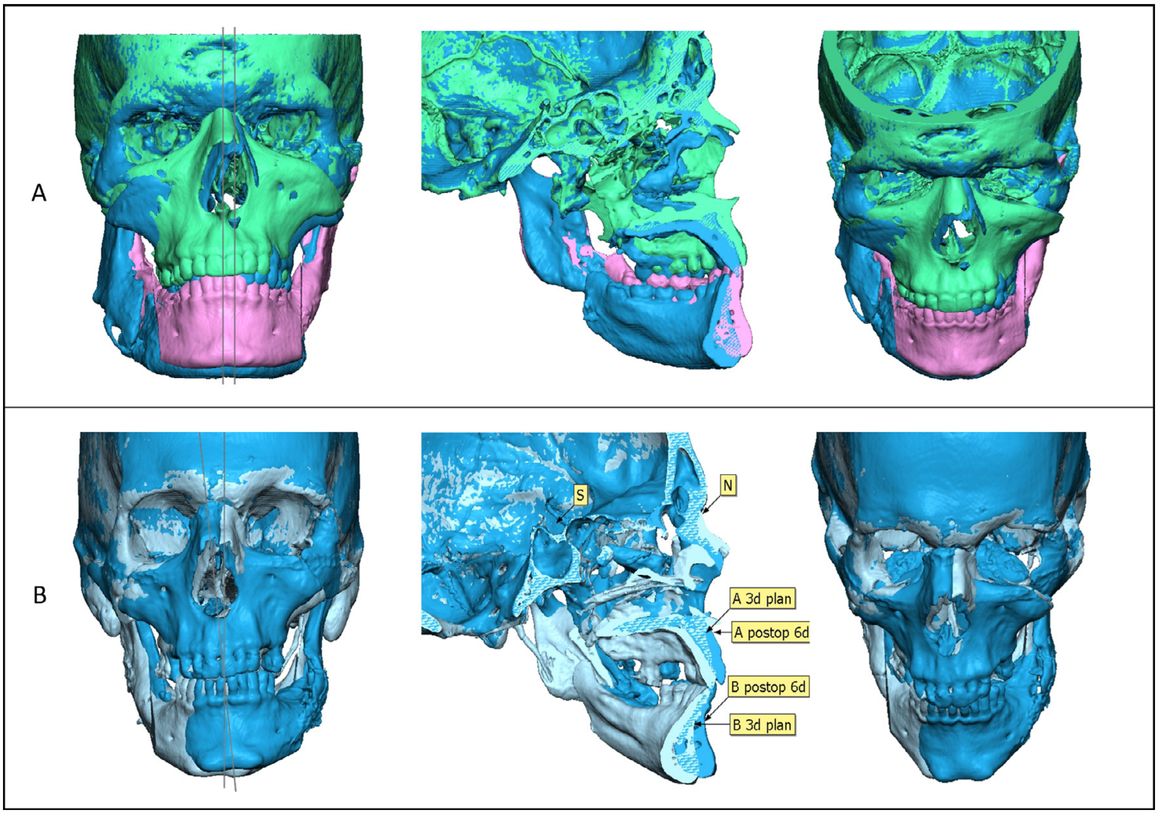

Fig. 3 Superimposed pictures of the 3D prediction and the early result.
A: Patient 1. Green: virtual 3D prediction.
B: Patient 2. Light blue: virtual 3D prediction.
Dark blue: The early result of the actual transplant.
Pink: Patient 1, mandible was not virtually planned.

Table 1 Differences in cephalometric measurements between virtual prediction and actual early result.

Patient 1		Horisontal (mm)*	Vertical (mm)**	Lateral (mm)
Maxilla	point A	-3.0	-5.2	
	Point UI			5 left
Mandible	point B	-5.0	-5.6	
	Point LI			2.1 left
		Virtual Plan (degrees)	Postoperative position (degrees)	Difference (degrees)
	SNA	96.5	98.8	-2.3
	SNB	94.3	95.9	-1.6
	ANB	2.2	2.9	-0.7
Patient 2		Horisontal (mm)*	Vertical (mm)**	Lateral (mm)
Maxilla	point A	4.0	0.1	
	Point UI			0.1 left
Mandible	point B	5.4	1.6	
	Point LI			2.3 left
		Virtual Plan (degrees)	Postoperative position (degrees)	Difference (degrees)
	SNA	87.5	91.5	-4.0
	SNB	83.5	86.5	-3.0
	ANB	4.0	5.0	-1.0

Point A: deepest point of the anterior contour of the maxillary alveolar process. Point B: deepest point on the outer contour of the mandibular alveolar process. Point UI: Upper incisive. Point LI: Lower incisive. SNA: Antero-posterior maxillary position. SNB: Antero-posterior mandibular position. ANB: Antero-posterior bimaxillary assessment.

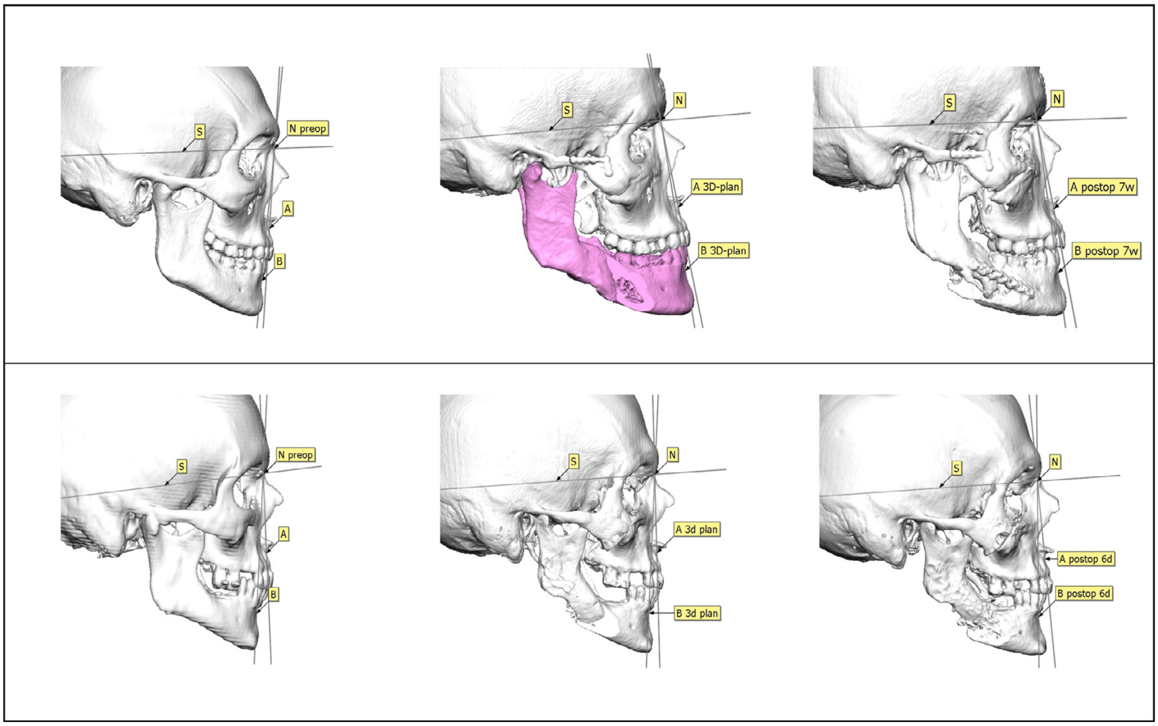

Fig. 4 Preoperative, prediction, and early result of cephalometric analyses.
Upper row from left to right: Donor for Patient 1, Patient 1 prediction, Patient 1 early result.
Lower row left to right: Donor for Patient 2, Patient 2 prediction, Patient 2 early result.

Discussion

We present here a comprehensive report of the use of recipient and donor-specific prefabricated osteotomy guides in composite FT and the use of real virtual transplantation just prior to the actual surgery. By creating this prediction, we could estimate precisely where the osteotomies should be placed and also to create accurate osteotomy guides for the donor and the patient. We conclude that the real virtual transplantation using 3D planning with patient and donor-specific osteotomy guides can result in near accurate prediction of the surgical results.

The 3D-CT image superimposition for evaluation of the accuracy of the 3D planning of FT poses several challenges because of the damaged skeletal tissues, head orientation and cephalometric landmark location. As it was not possible to use the natural head position (NHP) for head orientation, the NP plane was used in superimposition. The differences in skeletal linear and angular measurements of the virtually simulated predictions and the actual postoperative results of the two patients varied between 0.1–5.6 mm and 0.7°–4°. In spite of these discrepancies, the postoperative relationships between maxilla and mandible (angle ANB) in both patients were almost identical when compared to the predictions. In bimaxillary orthognathic surgery, the success criteria for computer-aided surgical simulations have been set for 2 mm for the linear and 4° for the angular differences[13,14]. Although the linear differences in this study were slightly larger, we conclude that the technique used in this study provides a reproducible 3D method for prediction of skeletal surgical outcome in FT. Given that the goal of FT is to improve function as well as form, the importance of orthognathic planning cannot be overstated with respect to optimizing harmony, profile, and occlusion[15,16].

Some clinics use prefabricated osteotomy guides for the recipient only [11], whereas other teams are able to use prefabricated osteotomy guides for both the donor and the recipient [10,12]. The benefits of prefabricated osteotomy guides in maxillofacial surgery have been proven and substantiated in several studies[17-19]. Hence, it is only logical that this technology has also found a role in FT surgery. In their cadaver model in 2013, Jacobs et al. showed that precise virtual planning could make the matching of donor and recipient skeletal elements more precise and allow a "snap-fit" reconstruction of the bone components[7]. In our patients, the whole process of designing and printing the donor-specific osteotomy guides took only 8 h which is in the time frame of normal facial procurement.

In 2015 Roche et al. published good results with 3D planning for their first FT patient[11]. For their virtual planning, they used CT-data extracted from the patient's son. In contrast, we decided to use data from random donor-models that had had a facial skeleton CT scan performed for other reasons. Thus, we did not need to perform any extra CT scans from anyone other than the actual donor. This enabled us to test different shaped and sized maxillary bones to fit the defect created by removal of the patient's damaged remnant maxillary bones.

Malocclusion can develop even if the computer-aided plan was executed precisely and the immediate postoperative occlusion would seem to be Angle class I [10,20]. It has been suggested that this problem is a result of the relation between mandibular condyle and its fossa while under anesthesia compared with conscious muscular activity [20]. Another possible contributing factor could be the lack of proprioceptive feedback and motor tone during the early phases of rehabilitation after the FT [10].

3D planning with patient and donor-specific osteotomy guides markedly reduced surgical time. Osteotomies for both the donor and patient were performed according to the guides and lasted only a few minutes. The inset of the transplanted donor bone required additional removal of posterior maxillary and pterygoid plate bones. For patient 1, the bony inset and plating was done according to the plan without any alterations to the osteotomies and lasted only 30 min. However, to allow for a margin of error the donor maxilla was planned to include an additional 2 mm of width that was not removed at the time of bone inset. This resulted in a slight misfitting of the maxilla and downward movement as shown by the cephalometric measurements. After analyzing the results, our team concluded that including additional bone in the donor maxilla is not advisable and that precise planning is preferable. Due to the inward cone shape, if the donor maxilla was too small, it would only be positioned slightly too cranially lowering the midfacial height by a few millimeters. For patient 2, our team did not notice the perioperative movement of the left zygomatic bone due to poor prior ossification. This resulted in poor fitting of the donor maxilla and we had to do some additional drilling in the radix area. After losing the exact cone shape of the transplanted maxilla it was then difficult to see its relative position in the patient's facial skeleton due to donor midfacial soft tissues blocking direct visualization. After analyzing this, our team concluded that the virtual preoperative planning is superior and more accurate than the surgeon's hands and the virtually designed plan should not be changed during the surgery unless absolutely necessary.

Conclusions

3D-planning, although not 100% accurate, simplifies the bony reconstruction in bimaxillary FT. Cephalometric results are more difficult to evaluate with bimaxillary transplants compared ortognatic surgery as intact bone is often lacking. However, good results are achievable with bimaxillary FTs as shown by our analysis. In Helsinki, we are fortunate in that it takes only eight hours to form the plan and deliver osteotomy guides to the operating theatre. This ensures that there is no delay to harvesting vital organs in a multiorgan harvest.

Although 3D planning and modeling can never replace good surgery, it makes these difficult and long surgeries easier and faster. In the future, we hope to see more technical solutions to make the planning process even more accurate and precise. Virtual reality software could prove to be of great assistance also in FT surgery.

Authors Roles

Conceptualization: Patrik Lassus, Arja Heliövaara, Andrew Lindford

Data curation: Atte Manninen, Patrik Lassus, Jani Horelli, Arja Heliövaara

Formal analysis: Jani Horelli, Arja Heliövaara

Investigation: Atte Manninen, Patrik Lassus, Jani Horelli, Andrew Lindford, Arja Heliövaara.

Methodology: Patrik Lassus, Arja Heliövaara.

Project administration: Patrik Lassus, Arja Heliövaara, Andrew Lindford.

Software: Jani Horelli

Pictures and measurements: Jani Horelli

Cephalometric analyses: Arja Heliövaara

Supervision: Patrik Lassus, Andrew Lindford, Arja Heliövaara.

Validation: Atte Manninen, Patrik Lassus, Arja Heliövaara, Andrew Lindford.

Visualization: Atte Manninen, Jani Horelli, Patrik Lassus

Writing ± original draft: Atte Manninen, Patrik Lassus, Arja Heliövaara, Andrew Lindford, Jani Horelli

Writing ± review & editing: Atte Manninen, Patrik Lassus, Arja Heliövaara, Andrew Lindford, Jani Horelli, Jyrki Törnwall, Tommy Wilkman, Karri Mesimäki

The Ethical Committee of Surgery of the University of Helsinki approved the use of the collected patient data for this study.

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