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Reconstruction of maxillary defects with free fibula flap assisted by computer techniques

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ABSTRACT

Objective: Free fibula flaps are widely used for maxillary reconstruction. The three-dimensional position of the fibula flap is very difficult to control in conventional operations based solely on the surgeon's experience. We aimed to improve this surgery by using computerized techniques.
Methods: Twenty-seven patients with maxillary tumors underwent maxillectomy and free fibula flap reconstruction in our department between 2011 and 2013. Virtual planning and surgical navigation were used for eight patients, and conventional surgery was performed in 19 patients. The three-dimensional fibular positions were evaluated in the two groups. Differences between the postoperative position of the fibular segments and the virtual plans were evaluated in the computer-assisted surgery group.
Results: The three-dimensional position of the fibula flap in the computer-assisted surgery group, including the vertical distance ($p = 0.013$), horizontal position ($p = 0.019$) and extension of the posterior end ($p = 0.041$), was significantly more accurate and nearer to the ideal position than that in the conventional surgery group. The average difference between the actual postoperative position of the fibular segments and the virtual plan in the computer-assisted surgery group was <5 mm.
Conclusion: Application of computer-assisted techniques such as virtual planning and surgical navigation significantly improve the clinical outcomes of maxillary reconstruction with free fibula flaps.

1. Introduction

The maxilla is the most important bony support of the midface skeleton and is critical for both esthetics and function. Thus, maxillary defects, such as those resulting from tumor resection, can cause severe functional and cosmetic deformities. Furthermore, maxillary reconstruction presents a great challenge for oral and maxillofacial surgeons. The free fibula flap, which was introduced by Hidalgo for mandibular reconstruction in 1989, is widely used in maxillofacial reconstruction. In 1993, Schusterman et al. reported the first midface reconstruction with a free fibula flap. The use of this flap with osseointegrated implants can provide esthetically and functionally satisfactory results in the long term (Yim and Wei, 1994; Nakayama et al., 1995; Kazaoka et al., 1999; Ferri et al., 2002). Thus, fibula flaps are ideal for maxillary reconstruction. We have reported excellent functional and acceptable esthetic results after maxillary reconstruction with free fibula flaps in 34 patients (Peng et al., 2005a). The success of maxillary reconstruction generally depends on the surgeons' experience, and although acceptable results are achieved in many patients with this technique, some degree of patient dissatisfaction does occur because the conventional surgical approach lacks an objective design process. Problems with the three-dimensional position of the fibular segments may be found on postoperative computed tomography (CT), and may not only lead to dissatisfactory esthetic outcomes but also influence subsequent implantation procedures.

Computer-assisted design and manufacture (CAD/CAM) techniques, such as virtual planning, rapid prototyping, reverse engineering and surgical navigation, are widely used in craniomaxillofacial surgery. Computer-assisted surgery is becoming increasingly popular in orthognathic surgery, post-traumatic orbital reconstruction and mandibular reconstruction with free fibula and deep circumflex iliac artery flaps (Metzger et al., 2007; Hirsch et al., 2009; Juergens et al., 2009; Wang et al., 2013). We aimed to improve the outcomes of maxillary reconstruction with free fibula flap and titanium mesh by using CAD/CAM techniques.

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2. Material and methods

2.1. Patient demographics

Between January 2011 and May 2013, 27 patients (12 men, 15 women) with maxillary tumors underwent maxillectomy and simultaneous reconstruction with free fibula flaps in our institute. The inclusion criteria were (1) maxillary pathology without facial muscle invasion, (2) requirement of total/subtotal maxillectomy, and (3) simultaneous maxillary reconstruction with free fibula flap. Patients with a history of tumor ablation and jaw reconstruction were excluded.

Eight patients underwent computer-assisted surgery, while in the other 19 patients, reconstruction was based on the surgeons' experience. In the computer-assisted surgery group, the mean patient age was 32.3 ± 4.7 years. Six patients had benign tumors, and two had malignant tumors. According to the Brown classification of maxillary and midface reconstruction (Brown and Shaw, 2010), five patients required class II reconstruction, and three patients required class III reconstruction. The mean age of the remaining 19 patients was 44.7 ± 2.9 years. Six of them had benign tumors, and 13 had malignant tumors. Class I, II and III reconstructions were required in 2, 15 and 2 patients, respectively. Patients in both groups were followed up for at least 6 months. Flap transplantations were successful in all 27 patients. No complications or local recurrence occurred in the computer-assisted surgery group, while in the conventional surgery group, two patients developed local recurrence, and one of them died of recurrent osteosarcoma (Table 1).

2.2. Virtual planning

Preoperative virtual planning was performed in the computer-assisted surgery group. CT of the head and neck, and lower leg were performed (field of view, 20 cm; pitch, 1.0; slice, 0.75 mm; 120Y280 mA). The CT data in DICOM format were imported to iPlan CMF (BrainLAB, AG, Germany). The tumor margins were marked with this software, so that the three-dimensional position of the tumor and its relationship to adjacent structures could be visualized accurately (Fig. 1). Next, virtual maxillectomy was performed with ProPlan CMF (Materalise, Leuven, Belgium) according to the clinical and three-dimensional radiographic findings. For Brown class I or II defects, a fibula reconstruction plan was created with the computer (Fig. 2). For Brown class III defects, a more complicated procedure was needed. In most patients with dissymmetry, mirror planning based on the healthy side was performed before the simulated fibula reconstruction. A three-dimensional resin stereomodel was printed, based on the mirrored plan through rapid prototyping techniques. The model was used to pre-bend two pieces of titanium mesh (0.6 mm, AO CMF, Synthes, Switzerland), which would be used to support the orbital floor and restore the maxillary contour (Fig. 3).

Table 1
Patient characteristics.

Groups	Computer assisted surgery	Traditional surgery
Number of patients	8	19
Sex (M/F)	5/3	7/12
Age (years)	32.3 ± 4.7	44.7 ± 2.9
Primary disease		
Benign tumor	6	6
Malignant tumor	2	13
Defect type		
Class I	0	2
Class II	5	15
Class III	3	2
Prognosis and outcome		
Local recurrence	0	2
Died of disease	0	1

2.3. Surgical procedure

In the computer-assisted surgery group, tumor resection and maxillectomy were performed according to the virtual plan, completely under the guidance of a computerized navigation system (BrainLAB, AG, Feldkirchen, Germany). The donor leg was ipsilateral to the maxillectomy site. The fibula flap was harvested, as described by Hidalgo (1989), simultaneously with the maxillectomy. A resin surgical plate was printed before the surgery, according to the virtual plan, and used as a template for fibula molding (Fig. 4). The fibula flap was transferred to the recipient site, and the pedicle was placed within a tunnel in the submandibular region to promote anastomosis. The three-dimensional fibular position was confirmed to match the position in the virtual plan by using the navigation system (Fig. 5).

In the conventional surgery group, tumor resection and fibula flap reconstruction were based on the surgeons' experience without any virtual planning or model design.

2.4. Outcome evaluation

Surgical outcomes were analyzed using CT after 6 months. The vertical distance between the maxilla and mandible, horizontal shift of the fibular segments, and position of its posterior end were compared between the two groups. The vertical distance determines whether there is sufficient space for implants/dentures, and the horizontal position significantly affects postoperative occlusion. The posterior end of the fibula is important because its overextension can limit jaw movement. We measured the difference between the vertical distance on the reconstructed side and that on the healthy side (Fig. 6); this difference was compared between the two groups by using a *t*-test. The horizontal fibular position was evaluated based on the relationship of the long-axis of the fibula with the actual or mirrored dentures, so that an unacceptable shift to the buccal or palatal side could be detected. We also evaluated the position of the posterior fibular end to ensure that there was no overextension of the reconstructed alveolar ridge compared with the healthy side. In the computer-assisted group, the fibula positions on the postoperative CT and virtual plan were compared using Geomagic Qualify/Studio (Geomagic, Cary, NC, USA) to indicate procedural reliability. All statistical analyses were performed using SPSS 17.0 (SPSS Inc., Chicago, Illinois, USA).

3. Results

In the computer-assisted surgery group, five patients had class II defects after tumor resection and subtotal maxillectomy. Free fibula flaps were used to reconstruct the defects according to the virtual plan. In the other three patients, who had class III defects, fibula flaps were used to reconstruct the alveolar ridge, and pre-bent titanium meshes were used to reconstruct the orbital floor and restore the maxillary contour. All flaps were successful. At a mean follow-up time of 21.0 ± 8.5 months (range: 6–36 months), no complications such as infection, exposure of titanium mesh, diplopia or enophalmos had occurred. Local recurrence or metastasis was not found in this group during the follow-up period. Symmetric appearance and ideal fibular segment position were achieved, as indicated by the three-dimensional CT reconstructions (Fig. 7). All patients were satisfied with their postoperative appearance.

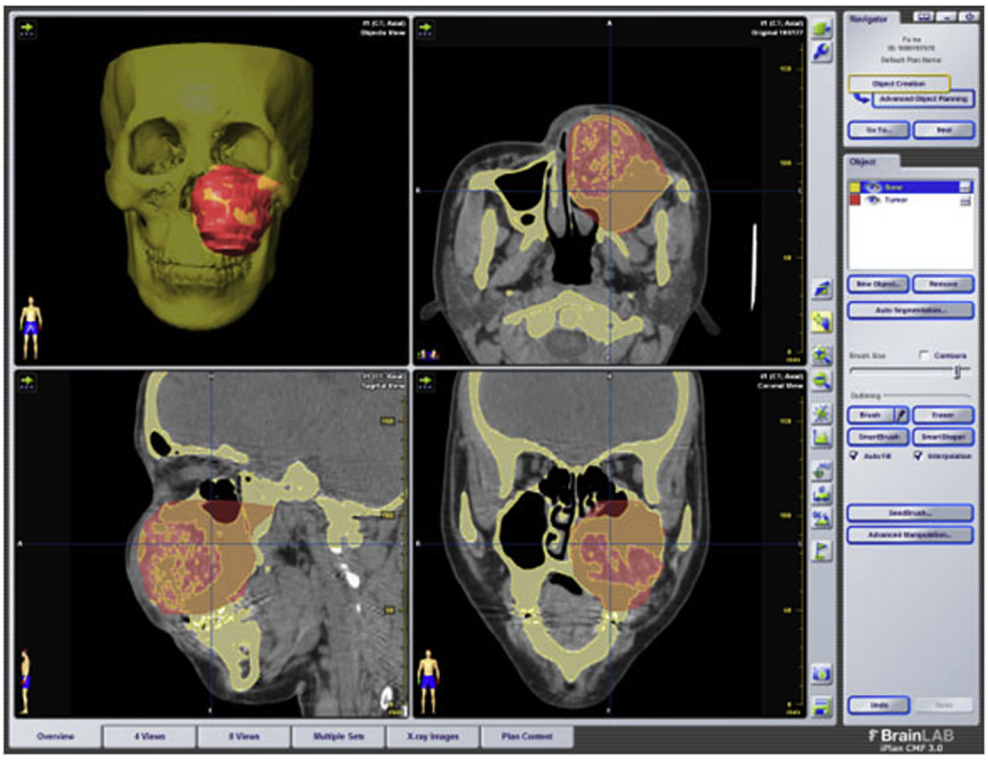

Fig. 1. Tumor mapping to visualize the tumor and adjacent structures.

In the conventional surgery group, no preoperative virtual planning was conducted. Tumor resection and maxillectomy were performed according to the clinical and radiological findings. The fibular position was determined on the basis of the surgeons' experience. In the 17 patients with class I or II defects, the fibula flaps were used to just restore the alveolar defects. In the two patients with class III defects, we also used a piece of non-vascularized fibula to support the orbital floor. All flaps were successful, but two patients developed local recurrence, one of whom died of osteosarcoma.

The difference between the vertical distance at the canine and first molars between the operated and unoperated sides was significantly better in the computer-assisted surgery group than in the conventional surgery group ($p = 0.013$; Table 2). In the former group, two of the eight patients had a horizontal fibular shift/rotation >5 mm (which can adversely affect dental restoration/implantation; Table 2). In the latter group, 14 patients had a horizontal shift >5 mm ($p = 0.019$). Thus, the horizontal fibular position was better in the computer-assisted surgery group, ensuring a better fit between the reconstructed maxilla and the lower dentition, and facilitating postoperative dental restoration/implantation. The posterior fibular end was overextended in 10 patients in the conventional surgery group (Table 2); some of these patients had difficulty with mandibular movements. Only one patient in the

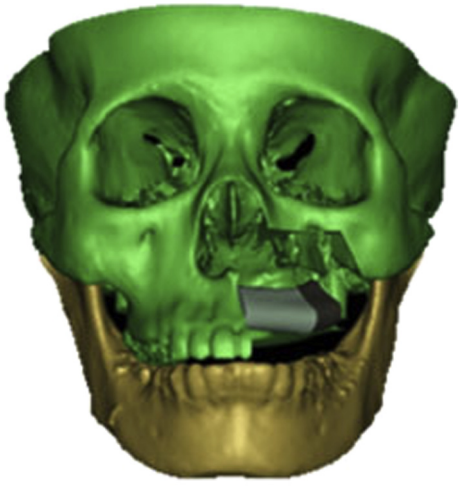

Fig. 2. Virtual planning of fibula reconstruction for a class II defect.

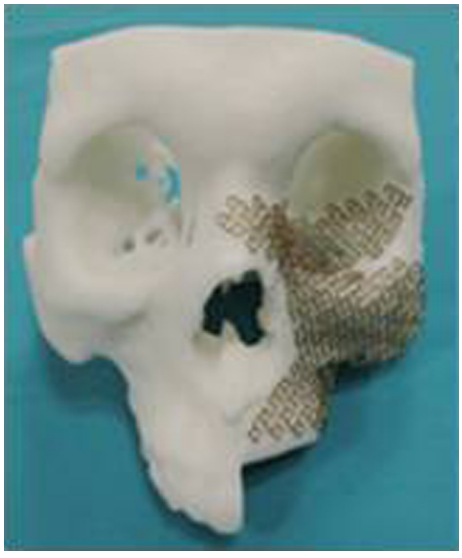

Fig. 3. Titanium mesh pre-bent on a printed 3D resin model.

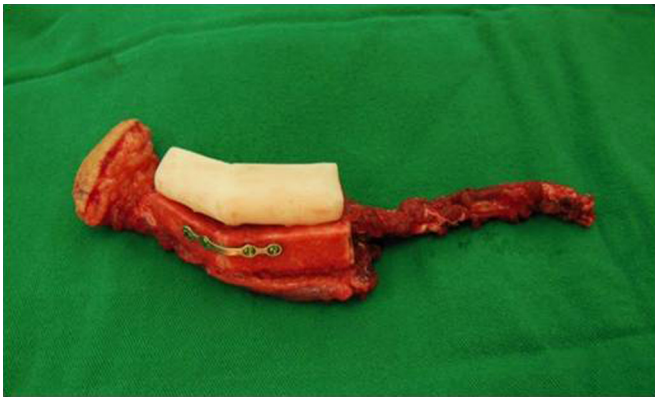

Fig. 4. A resin template used for flap molding.

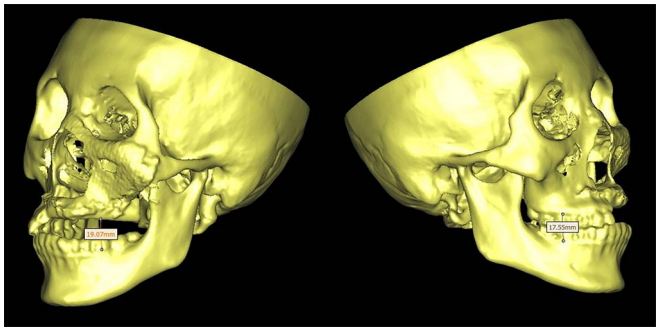

Fig. 6. Measuring the vertical distance on the reconstructive side and the healthy side.

computer-assisted surgery group had fibular overextension ($p = 0.041$).

The postoperative three-dimensional images and the preoperative virtual images of the eight patients in the computer-assisted group were registered and superimposed onto each other using Geomagic Qualify. This program recognizes corresponding points in the two images and highlights the superimposed image with different colors based on the distance between the corresponding points. The resulting error-grade color map gives a direct visualization of the match between the virtual plan and actual postoperative state (Fig. 8). In all eight patients, the error-grade color map of the reconstructed fibula showed a difference of <5 mm.

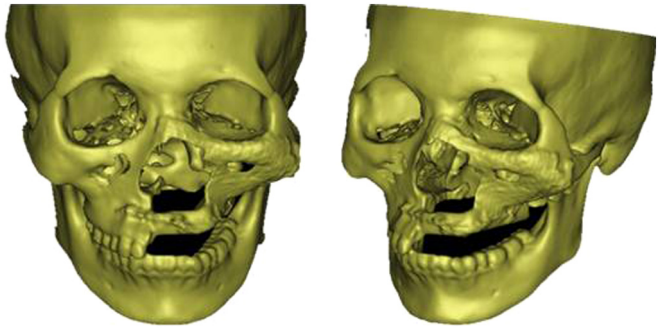

Fig. 7. Postoperative CT images show that symmetry and ideal positioning of the fibular segments has been achieved.

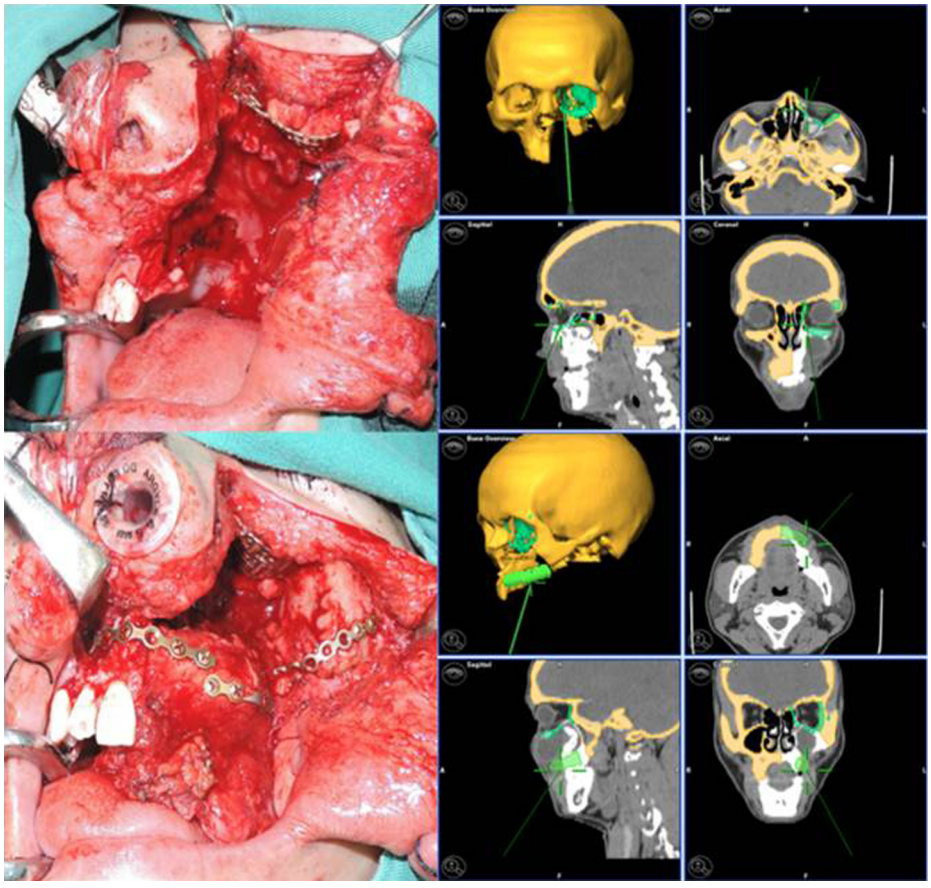

Fig. 5. The position of the fibula and titanium mesh are confirmed using the navigation system.

Table 2
Three-dimensional position of the fibula segments in the two groups.

	Computer assisted group	Traditional surgery group	*p* value
Number of patients	8	19	
Change of vertical distance (mm)	2.82 ± 1.22	6.13 ± 3.12	0.013
Horizontal shift (>5 mm)	2 (25%)	14 (73.6%)	0.019
Over extension of the posterior end of fibula (*n*)	1 (12.5%)	10 (52.6%)	0.041

4. Discussion

Maxillary defects resulting from tumor ablation or trauma may cause severe functional and esthetic deformities, and are challenging to treat. In 1993, Sadove and Powell used free fibula flaps to reconstruct maxillary–mandibular defects. At the same time, Schusterman et al. (1993) used free fibula flaps for orbital and midface reconstruction. The most important goals of maxillary reconstruction include: (1) obliteration of the defect, (2) restoration of function, particularly, speech and mastication, (3) structural support for reconstruction of external facial features and (4) esthetic reconstruction of external facial features (Peng et al., 2005a). Several studies have reported that the fibula is very compact and suitable for dental implants, which renders it suitable for functional maxillary reconstruction (Frodel et al., 1993; Futran and Haller, 1999; Mao et al., 2001a, 2001b; Futran et al., 2002). Therefore, free fibula flaps are widely used for maxillary reconstruction.

Even so, some problems were found on the follow-up clinical and CT examinations (Fig. 9). It was difficult to properly control the fibular position on the basis of the surgeons' experience alone. In some patients, the vertical distance on the operated side was too small compared with the contralateral side, leaving insufficient space for dental implants/dentures. It should be noted that too wide a space also makes functional dental rehabilitation difficult. In this research, the difference in the vertical distance between the reconstructed and healthy sides (i.e., the change in vertical distance) was 6.13 ± 3.12 mm in the conventional surgery group. In eight patients in this group, the vertical distance was significantly larger on the operated side than on the contralateral side, and the fibula was too far away for good occlusion with a dental prosthesis. In another six patients, however, there was not enough vertical space for dentures or implants because the fibula was too low. An acceptable vertical distance was achieved in only five patients. In 14 of the 19 patients (>70%) in this group, the fibular segments deviated to the buccal (10 patients) or palatal (4 patients) side because the fixation was performed solely on the basis of the surgeons' experience. In these patients, the fibular axis did not fit the contour of the ideal dental arch horizontally, which could render implant or conventional dental prosthesis placement difficult. Moreover, 10 patients had restricted mouth opening after the surgery. In these patients, the reconstructed fibula was too long and extended to the coronoid process, thus disturbing mandibular movement.

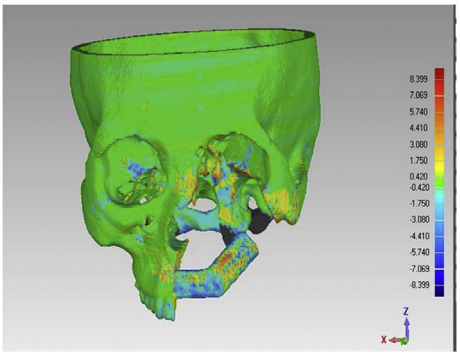

Fig. 8. Color-coded match percentage between the virtual and postoperative images.

Besides the limitations in oral function, the esthetic outcome and complications resulting from the orbital defect are also a challenge for maxillofacial surgeons. For class III defects in the conventional surgery group, we used a vascularized fibula to reconstruct the alveolar ridge, a muscle (flexor hallucis longus) to fill up the maxillary sinus space and a piece of non-vascularized fibula to support the orbital floor. Since the structure and contour of the orbital floor are complex, it was rarely possible to maintain the orbital position and volume. Moreover, since the maxillary sinus space was filled in with soft tissue without any bony support, the suborbital tissues were invariably either depressed or prominent compared with the opposite side.

Computer-assisted surgery offers substantial improvements in the esthetic and functional outcomes of numerous surgical procedures. The surgery can be simulated on a computer (virtual planning) and on a stereomodel prepared using a rapid prototyping technique. Commercial software such as ProPlan CMF and Mimics (both developed by Materialise) are the most widely used tools for this procedure, and provide functions such as segmentation, osteotomy, repositioning, data analysis and reconstruction. The computer navigation technique builds a 'virtual-reality' bridge for the surgeons, especially, for bony surgeries such as osteotomy, orthognathic surgery, fracture reduction and bone flap reconstruction (Ewer et al., 2005; Yu et al., 2013). The navigation system can provide 'real-time' and three-dimensional visualization during surgery. Unlike conventional reconstructions, which are based on the surgeons' experience, the virtual plan can provide a quantified design for both tumor resection and bone reconstruction. The navigation system helps the surgeon to match the preoperative design by indicating the correct osteotomy planes and bone positions. Generally, the computer-assisted process, including virtual planning and surgical navigation, significantly improves surgical accuracy. Many authors (Juergens et al., 2009; Zhou and Shang, 2010; Roser et al., 2010; Wang et al., 2013; Foley et al., 2013) have applied computer-assisted techniques to mandibular reconstruction with free fibula and deep circumflex iliac artery flaps. Based on these reports and our previous experience (Mao et al., 2001a, 2001b, 2003; Peng et al., 2003a, 2003b, 2004, 2005b, 2011; Liu et al., 2009), we found that computer-assisted surgery can match the reconstructed maxillofacial area to within 5 mm of the contralateral side.

However, few studies have investigated computer-assisted techniques for maxillary or midface reconstruction. Lethaus et al. (2010) reported a case of maxillary and orbital floor reconstruction with a microvascular fibula graft and an individualized titanium mesh based on a virtual plan and guided by a resin template during the surgery. A navigation system was not used, and the outcome could not be evaluated objectively. Nakayama et al. (2004) and Kokemueller et al. (2008) reported on patients who underwent ablative surgery for maxillary cancer and reconstruction using three-dimensional orbitozygomatic skeletal models with titanium meshes and soft-tissue free flaps for complex midface defects. Excellent results were achieved esthetically, but only a few patients

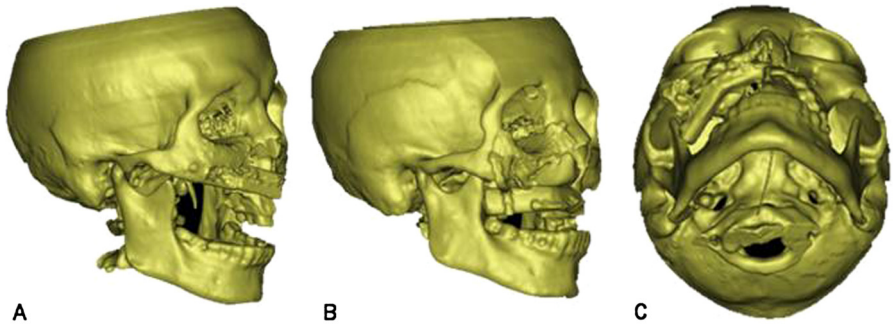

Fig. 9. Problems in the position of the fibula. A) Overhigh position of the fibula, leading to an excessive vertical distance; B) Overlow position, leading to less space for denture restoration; C) Deviation to the buccal side and overextension.

could receive conventional dental restoration. Modabber et al. (2013) reported on maxillary–zygomatic reconstructions with deep circumflex iliac artery flaps by virtual planning and template model, which can significantly improve the clinical outcome. Recently, Rohner et al. (2013) reported a case with an extensive defect of the left cranio-maxillofacial area due to radical tumor resection. A prefabricated fibula flap and reconstruction plate were used for reconstruction with the application of computer-aided design and stereolithographic models. They also used a patient-specific guide as a transformer in the operation. These procedures improve the patient outcome and the intraoperative efficiency.

To our knowledge, there are no systematic studies on maxillary reconstruction with free fibula flaps and individualized titanium meshes, using computer-assisted techniques, including virtual planning, stereomodel and surgical navigation. Our research included eight such patients, and is perhaps the largest series comparing computer-assisted surgery with conventional surgery to determine if the former has comparable outcomes to and can help resolve the problems associated with the latter. In the three patients with class III defects, mirror plans based on the median sagittal plane provided an individualized symmetric appearance. The titanium mesh, which is flexible and compatible with tissue, was pre-bent on the stereomodel to fit the individual contour of the orbital floor and suborbital area. One piece of the mesh supported the new orbital floor and maintained the orbital contents and volume. The other piece covered the front wall of the maxilla to reestablish the contour of the suborbital and perinasal areas. This procedure improved the postoperative appearance of the patients and achieved the esthetic goal of maxillary and midface reconstruction. Every patient was satisfied with his/her appearance. The postoperative images were also quite symmetric and acceptable.

The computer-assisted design showed its superiority not only in the reconstruction part but also in the process of diagnosis and tumor resection. Because of the complex anatomic structures of the mid-face, it is very difficult to identify the margin of the tumor based on the conventional two dimensional radiographs, especially for malignant cases. Thus the tumor resection and osteotomies relied on the experience of the surgeon in planning and tailoring the operation according to their intra-operative findings. In our study, two patients in the traditional group presented with local recurrence within the follow-up period. On the other hand, tumor mapping slide by slide was performed on iPlan CMF for all the eight patients in the computer-assisted group, creating a three-dimensional image of the tumor and adjunct structures. According to this three-dimensional imaging, the virtual plan for tumor resection was formulated. Each osteotomy plane was guided by the navigation system to confirm the virtual plan during surgery. Intraoperative frozen section analysis was used to ensure clear surgical margins. The frozen section results were negative in all eight cases in the computer-assisted group, and there were no intraoperative changes to the planned areas of resection. Such changes would mean that the preoperative reconstruction plans require adjustment or major changes. During the follow-up period, no patient of this group presented with local recurrence. Thus the procedure for tumor mapping and virtual osteotomy was proved to be feasible and reliable.

Our research has proved the feasibility and advantages of computer-assisted techniques in maxillary reconstruction with free fibula flaps. However, this is a developing technique and some limitations and disadvantages remain. Systematic errors can accumulate during step-by-step work. For example, the mirror plan is a subjective manipulation by the virtual surgeon. There is no 'perfect' or 'right' position for the fibular segments because virtual planning is experience-based work. Considering the navigation system, the systematic error of registration process remains inevitable. Moreover, all the virtual plans were based solely on bony tissue in the CT scans. However, soft tissue should also be considered during the actual operation. Thus, differences or errors may occur in the postoperative evaluation process. Despite this, our research demonstrates the superiority of computer-assisted surgery over conventional reconstruction, with an acceptable error margin of <5 mm.

5. Conclusion

Compared with conventional maxillary reconstructions with free fibula flaps, computer-assisted techniques such as virtual planning and surgical navigation significantly improve the accuracy of positioning of fibular segments. This procedure will enhance the functional and esthetic outcomes of maxillary reconstruction with free fibula flaps.

Conflicts of interests

None of the authors has a financial interest in any of the products, devices, or drugs mentioned in this manuscript.

Acknowledgment

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