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Post-traumatic maxillofacial reconstruction with vascularized flaps and digital techniques: 10-year experience

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Abstract. The aim of this study was to present a treatment protocol for the individual repair of post-traumatic maxillofacial bone defects with vascularized flaps assisted by digital techniques. This study reviewed 20 patients with post-traumatic maxillofacial bone defects who underwent reconstruction with composite vascularized bone flaps assisted by digital techniques between April 2009 and July 2019. Preoperative computed tomography (CT) data were imported into ProPlan CMF software to complete virtual fracture reduction and reconstruction. Surgical navigation, three-dimensionally (3D) printed surgical plates, and prefabricated titanium mesh/plates were used to guide the actual surgery. All patients underwent open reduction and internal fixation and reconstruction surgery in one stage. CT data obtained at 1 week postoperative were imported into Geomagic Control software to evaluate the accuracy of the virtual surgical plan. The mean follow-up interval was 24 months (range 6–96 months). Donor and recipient site morbidity and second-stage procedures to rehabilitate the dentition and cosmetic organs were recorded. The flap success rate was 100%. Nine patients had deep circumflex iliac artery flaps and eleven patients had fibula flaps. The accuracy of computer-assisted surgery was 4.4 ± 0.8 mm. There were no postoperative complications. This study is novel in presenting a treatment protocol for individual computer-assisted reconstruction for post-traumatic maxillofacial bone defects with vascularized flaps.

Key words: post-traumatic defects; surgical navigation; computer-assisted surgery; mandibular reconstruction; maxillary reconstruction.

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Maxillofacial bone defects often result from oncological resection, trauma, and infection[1,2]. Due to the relatively low incidence rate of post-traumatic bone defects, most of the studies on maxillofacial reconstruction have focused on bone defects resulting from oncological resection[3]. Nevertheless, post-traumatic maxillofacial bone defects have several unique characteristics that should be considered when conducting reconstructive surgery, and such defects are worth considering as an isolated research topic. Regarding patient characteristics, patients with post-traumatic defects are relatively young and have higher expectations for their oral function and aesthetic appearance. During preoperative surgical planning, the lack of pre-injury imaging and concomitant delayed bone fracture have challenged the existing protocols for computer-assisted reconstructive surgery. When considering the intraoperative techniques, how to conduct simultaneous fracture reduction and reconstruction in a minimally invasive way is a complicated issue for maxillofacial surgeons.

The goal of post-traumatic reconstruction is to individually restore the aesthetic appearance and create a stable pre-prosthetic framework for implant reconstruction. Based on the complexity of reconstruction for post-traumatic defects, digital surgical techniques are used widely to achieve individualized, minimally invasive, and functional reconstructions. Due to the unique characteristics mentioned above, a unique and customized treatment protocol for post-traumatic maxillofacial bone defects is also required.

The aim of this study was to present a treatment protocol for the restoration of post-traumatic maxillofacial bone defects with vascularized flaps assisted by digital techniques. This was done by summarizing and evaluating our clinical experience of reconstruction for post-traumatic bone defects over the past 10 years.

Table 1. Patient and treatment characteristics.

Characteristics	
Sex (*n*)	
Male	16
Female	4
Age (years)	
Average	34.7
Range	19–60
Mechanism of injury (*n*)	
MVA	11
Other (falling, crashing)	9
Time after injury (months)	
Median	9.7
Range	0.5–36
Location of bone defect (*n*)	
Maxilla	11
Mandible	9
Type of bone defect (*n*)	
Unilateral	11
Bilateral	9
Type of vascularized flap (*n*)	
Fibula flap	11
DCIA flap	9
Computer-assisted technique (*n*)	
Surgical navigation	8
3D-printed surgical guide	5
Prefabricated titanium plate/mesh	7
Anastomoses (*n*)	
Submandibular	15
Temporal	2
Intraoral	3
Deviation from virtual plan (mm)	
Mean	4.4
Standard error	0.8
Secondary surgeries (*n*)	
Dental implants	10
Cosmetic organ reconstruction	7
Follow-up interval (years)	
Average	24
Range	6–96

MVA, motor vehicle accident; DCIA, deep circumflex iliac artery (supplies the iliac crest); 3D, three-dimensional.

Patients and methods

Patient demographics

This study retrospectively reviewed 20 patients (16 male and 4 female, with an average age of 34.7 years) who underwent reconstruction with vascularized flaps assisted by digital surgical techniques for maxillofacial bone defects following traumatic injuries. The patients were treated at Peking University School and Hospital of Stomatology between April 2009 and July 2019. The following data were collected: age, sex, mechanism of injury, defect range, adjacent bone fracture, concomitant soft tissue defects, types of vascularized flap used, recipient vessels used, second-phase reconstruction, and follow-up intervals (Table 1). The varied and complicated scope of the defects are shown in Fig. 1.

The Ethics Committee of Peking University School and Hospital of Stomatology approved this study (PKUSSIRB-201949138), and all participants signed an informed consent agreement.

Methods

In all cases, surgeries were performed according to the virtual plan and under the guidance of a computerized navigation system (Brainlab AG, Feldkirchen, Germany), pre-fabricated titanium plates, or three-dimensionally (3D) printed surgical plates (Byteking, Beijing, China). Preoperative maxillofacial non-contrast-enhanced computed tomography (CT) scans were acquired before surgery (helix with 1.25-mm slice thickness) (GE BrightSpeed 16-slice CT scanner; GE Healthcare, Chalfont St Giles, Buckinghamshire, UK) (Fig. 2).

Virtual surgical planning

For cases up to and including 2010 (2009 and 2010), the spiral CT data were imported into SurgiCase CMF version 5.0 software (Materialise, Leuven, Belgium); for cases from 2011 onwards (2011–2019), ProPlan CMF software was used (Materialise NV, Leuven, Belgium). For unilateral defects and fractures, the non-affected side was mirrored according to the midsagittal plane to serve as reference data for the reduction and reconstruction[4] (Fig. 3A–C). For bilateral defects across the midline, where the ‘mirror’ technique cannot be used, the patient’s stereolithography (STL) file was imported into a database that includes 552 3D craniomaxillofacial models of normal Chinese adults, developed at Peking University School and Hospital of Stomatology and Tsinghua University. After calculating the deviation of each Euclidean distance between each paired feature that existed in the patient and normal model, the most similar model in the database was exported as the reference data and served as the template for reconstruction[5] (Fig. 4A–C).

For maxillary defects involving mechanical bone buttressing and mandibular defects involving dentition defects, the deep circumflex iliac artery (DCIA) flap was preferred for shaping and later dental implant placement due to its ample height and thickness (Fig. 3C, Fig. 4D). For maxillary and mandibular defects with larger spans, the fibula flap was preferred due to its sufficient length.

Surgical navigation was preferred in cases with maxillary defects, due to a relatively stable position and delayed zygomatic fracture reduction. The 3D-printed surgical guide plate was preferred in cases with mandibular defects in order to reposition the ramus and maintain the defect range. Harvesting, shaping, and positioning of the vascularized flap were assisted by prefabricated titanium plates and mesh and surgical guide plates (Fig. 3D).

Surgical procedure

All patients underwent open reduction and internal fixation and reconstruction surgery in one stage. The fractured bone segments were exposed and reduced using the subsidiary, coronal, submandibular, and intraoral approaches. If a malocclusion remained after reduction, a Le Fort I osteotomy and sagittal split ramus osteotomy (SSRO) were used to correct the malocclusion. The fibula or DCIA flap was harvested and shaped under the guidance of a 3D-printed resin surgical plate. The 3D flap position was confirmed to match the position in the virtual plan using the navigation system, fabricated titanium plate, or 3D-printed resin surgical plate

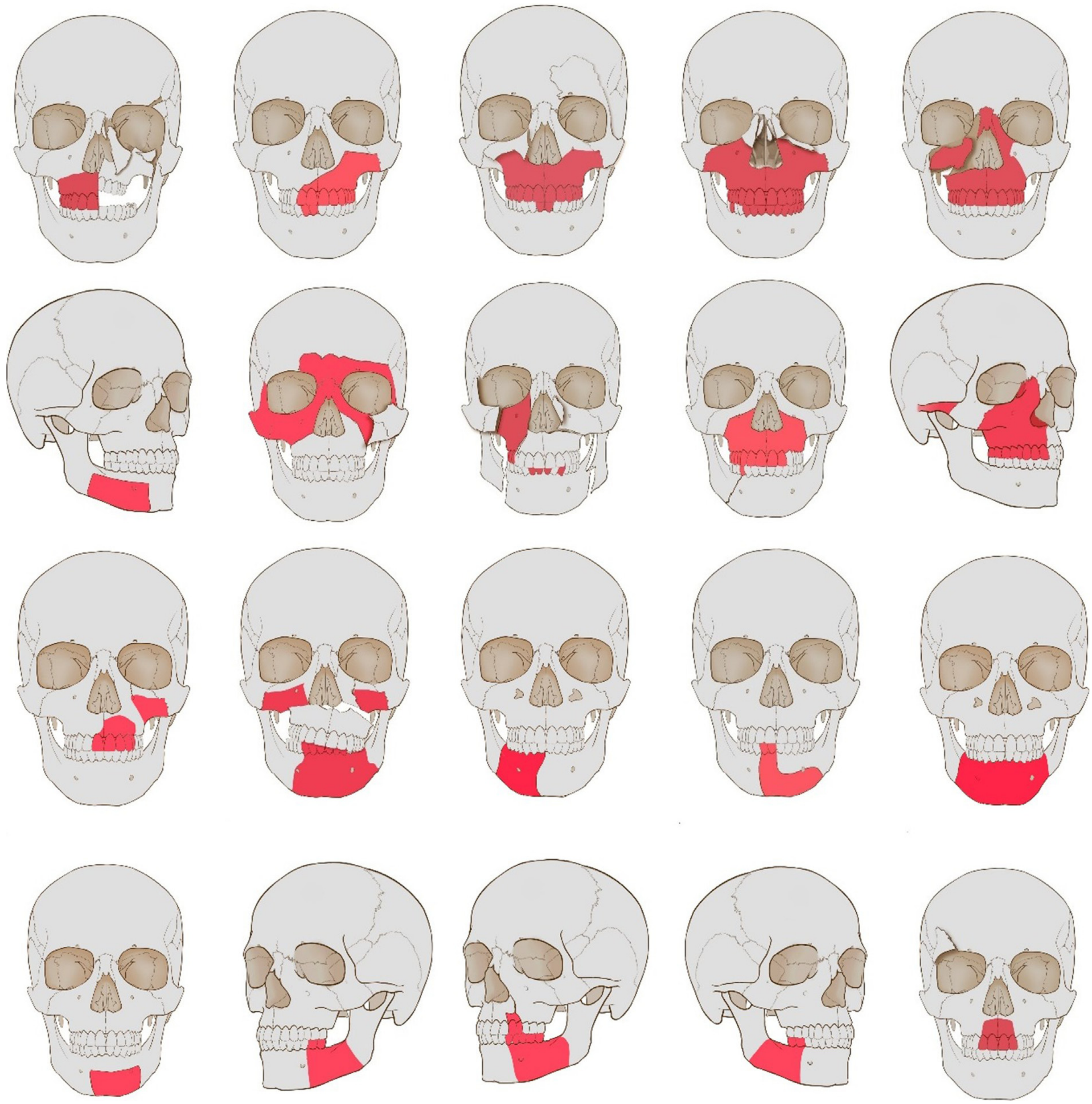

Fig. 1. Scheme showing the scope of the post-traumatic defects (in red) in the patients included in this study.

(Fig. 3E). Anastomoses were then conducted through a submandibular approach, superficial temporal approach (Fig. 3F), or intraoral anastomosis.

Outcome evaluation

All patients underwent CT scans at 1 week after surgery. The accuracy of the virtual surgery was analysed by comparing the postoperative 3D images with the virtual surgical plan. The postoperative 3D images and virtual surgical plan were created as STL files, imported into Geomagic Control version 12.0 software (3D Systems, Inc., Morrisville, NC, USA), and then superimposed by automatic registration. The bone defect area was selected for the colour-map comparison. The software automatically recognizes the corresponding points from the two files and highlights the superimposed image with different colours according to the distance between the corresponding points. After the comparison, a colour-graded error map was generated to show the matching deviation between the two files, where a specific colour indicated each grade of deviation. The distances from the corresponding points in the two files were also automatically measured and analysed for a comparison report. The average distance was considered as the error of the virtual surgery (Fig. 5).

All patients were followed up clinically and radiologically for at least 6 months. Postoperative complications such as plate breakage, plate exposure, infection, and malocclusion were evaluated and recorded. The data management and analysis were performed using IBM SPSS Statistics version 24.0 (IBM Corp., Armonk, NY, USA).

Results

The overall flap success rate was 100%. The average surgery time decreased from 8.4 hours in 2009–2015 to 7.5 hours in 2016–2019. Nine patients had DCIA flaps and 11 had fibula flaps. The recipient

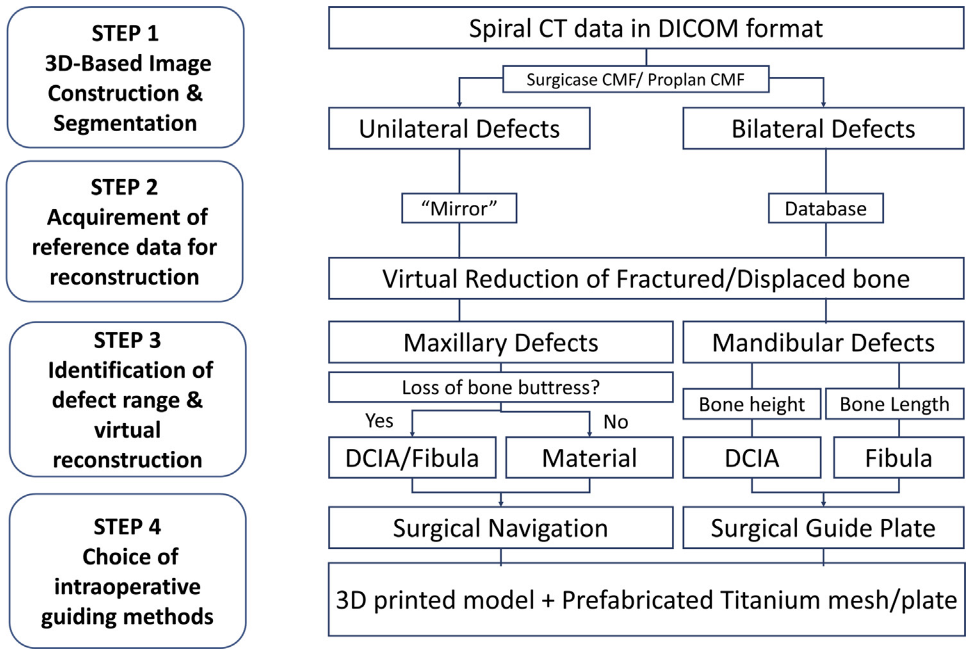

Fig. 2. Algorithm for computer-assisted post-traumatic maxillofacial bone defect restoration. (DCIA, deep circumflex iliac artery).

vessels were the facial artery and facial vein in 15 patients, the superior thyroid artery and facial vein in three patients, and the superficial temporal artery and vein in two patients. Intraoral anastomosis was used in three patients. The accuracy of computer-assisted surgery was 4.4 ± 0.8 mm. The average follow-up was 24 months (range 6–96 months). No patients suffered recipient site complications such as infection, iatrogenic facial nerve damage, and flap resorption, or donor site complications such as limp. Ten patients underwent dental implantation and seven patients completed sequential plastic surgeries rehabilitating oral function and cosmetic organs. All patients were satisfied with their postoperative appearance (Fig. 3G, H; Fig. 4E, F).

Discussion

Post-traumatic maxillofacial bone defects have unique characteristics that are different from those of bone defects resulting from oncological resection. First, the range of the defects is unpredictable and irregular. As shown in Fig. 1 and Table 1, the bone defect was different in each patient and 80% of the cases had adjacent bone fractures accompanying the bone defect, which could not be uniformly classified using the current classifications for maxillary[6] and mandibular[7] defects. Second, most of the patients have concomitant soft tissue and cosmetic organ loss, which require secondary procedures to rehabilitate the aesthetic appearance and normal oral function. Third, achieving an optimal result is crucial for trauma patients as they are generally young, without comorbidities, and have higher expectations than oncological patients. Based on these factors, the goal of post-traumatic bone defect repair is to individually restore the skeletal construct and deliver abundant soft tissue bulk in preparation for secondary functional reconstruction with minimal additional trauma.

Unpredictable and irregular post-traumatic bone defects require careful preoperative planning to ensure predictable reconstruction results. Nowadays, digital surgical techniques are commonly used in oral and maxillofacial reconstruction surgeries since they have better clinical results than traditional surgery[8–10]. The most fundamental step in preoperative planning is to obtain appropriate reference data to guide virtual reconstruction and especially bone fracture reduction in post-traumatic cases. For patients with unilateral fractures and defects, the healthy side can be used as a natural reference for the affected side, which is also known as the 'mirror' technique. This technique has been shown to be an effective approach in preoperative planning[11,12]. For bilateral fractures and defects across the midline, the 'mirror' technique cannot be applied. Yao et al.[5] have reported a method for the identification of the most corresponding skull model from a 3D craniomaxillofacial database of normal Chinese people that can be used as reference data in such cases. In this study, the STL files from patients with bilateral defects across the midline were matched with the 3D craniomaxillofacial models of 552 normal Chinese adults so as to identify the most corresponding one as the reference for fracture reduction and defect repair.

Virtual fracture reduction and the bone defect range can be determined from appropriate reference data. When contemplating the reconstruction approach, it is necessary to consider the area and range of the defect, other organ systems involved, nutritional status, and previous operative interventions. Non-vascularized bone grafts remain an excellent option for the management of small bone defects surrounded by well-vascularized soft tissue[13]. Artificial implants are suitable for midfacial reconstruction without mechanical loading[14]. Regarding large bone defects in areas under mechanical loading with poor recipient site conditions, vascularized bone flaps are recommended to avoid tissue contraction, scarring, bone misalignment, and bone resorption[6].

In this study, nine patients had DCIA flaps and 11 patients had fibula flaps. An adequate height for dental implant placement, mala projection, suitability for areas under mechanical loading, and use in orbital reconstruction are the greatest advantages of the DCIA flap[15]. Furthermore, the natural curve and contour of the iliac crest are more effective in the rehabilitation of the anatomical features in the defect area when compared to the fibula flap. Potential disadvantages of the DCIA flap include the thick subcutaneous layer and short

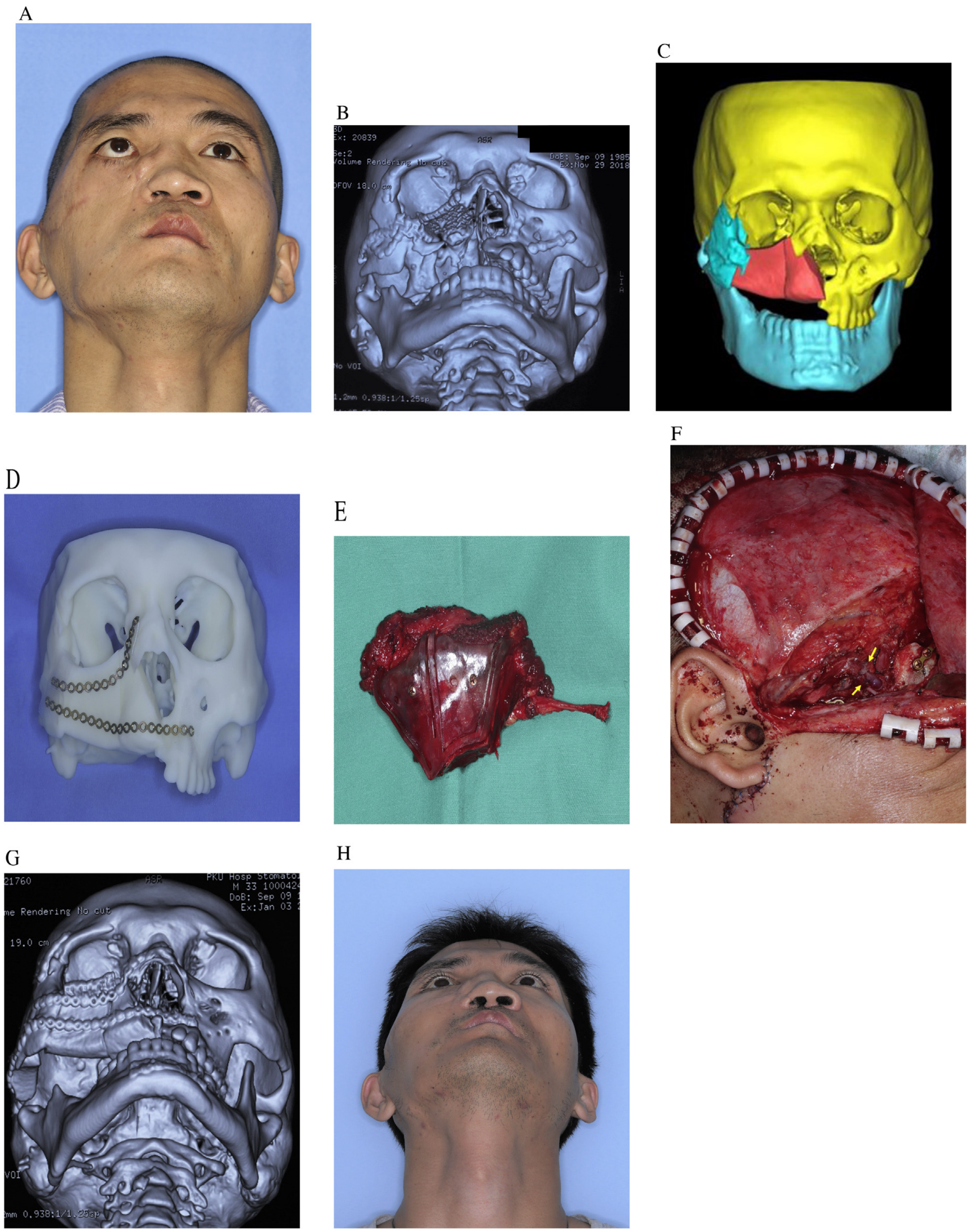

Fig. 3. Computer-assisted reconstruction for a post-traumatic unilateral maxillary defect. Preoperative (A) photograph and (B) CT scan of the patient. (C) Virtual reconstruction with a DCIA flap. (D) Pre-bent titanium plate based on the 3D-printed skull model. (E) DCIA flap harvesting and shaping guided by the 3D-printed surgical guide plate. (F) Anastomosis between the DCIA and superficial temporal artery, and between the deep circumflex iliac vein and superficial temporal vein (arrow). The patient at 9 months postoperative: (G) CT scan, (H) photograph.

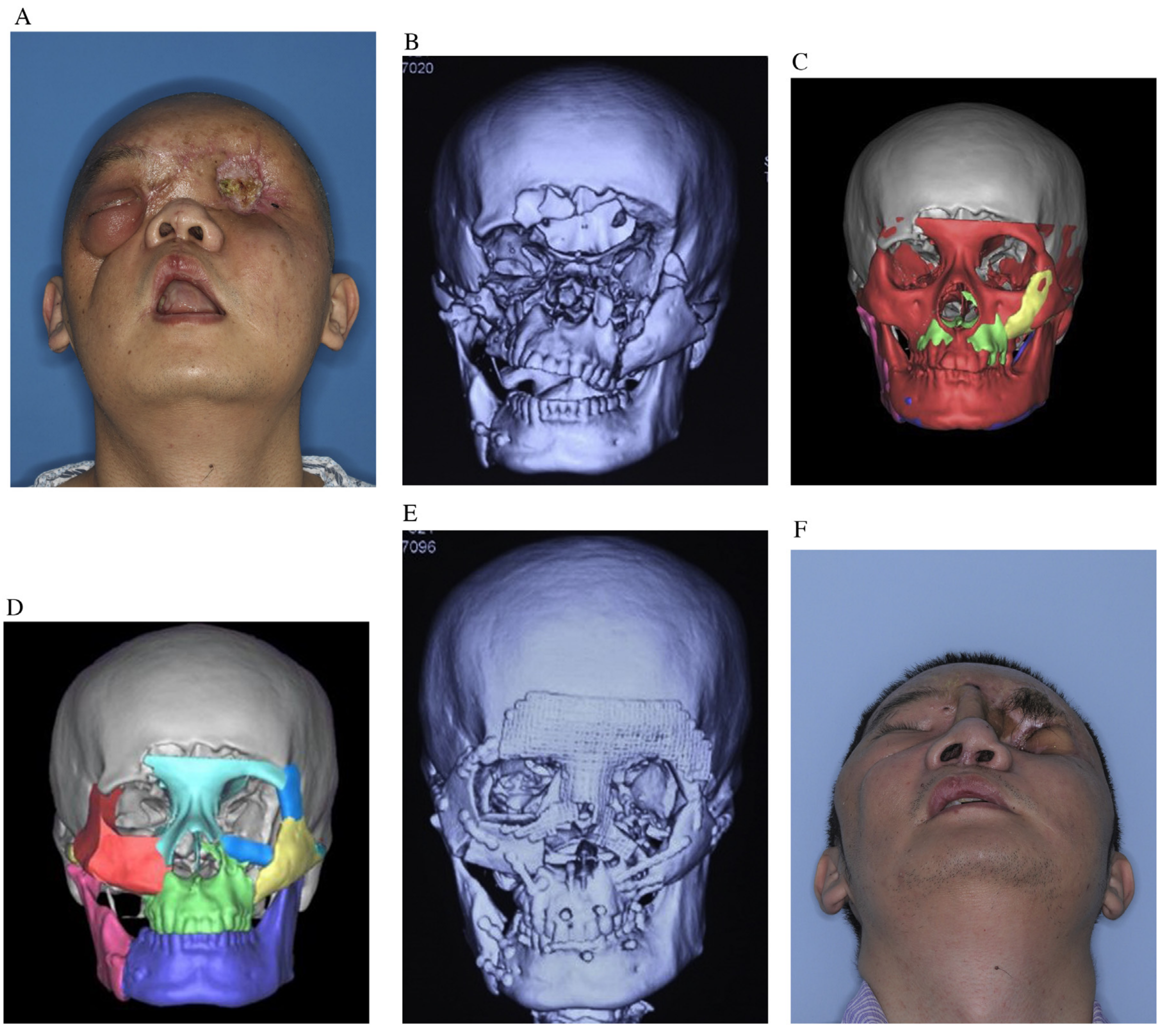

Fig. 4. Reconstruction according to reference data obtained from the database for a bilateral defect and fracture across the midline. Preoperative (A) photograph and (B) CT scan of the patient, showing a large area of bone defect including the frontal bones, naso-orbital-ethmoid bones, right zygoma, part of the left zygoma, and anterior skull base. (C) Virtual reconstruction according to the reference data obtained from the database. (D) A titanium mesh prosthesis was used to repair the frontal naso-orbital-ethmoid defect; a DCIA flap was used to reconstruct the right zygoma; a non-vascularized bone graft was used to rebuild the left orbit. (E) Postoperative CT scan after reconstruction with the DCIA flap and titanium mesh. (F) Photograph of the patient at 1.5 years postoperative.

pedicle[16]. For defects with larger spans, the length of the DCIA flap is not sufficient, leaving the fibula flap as the best choice. A large and reliable skin paddle can be used to harvest up to 26 cm of long straight fibula bone[17]. When choosing the appropriate strategy for vascularized reconstructions, the scope of the defect and balanced consideration of the aesthetic appearance and oral function should be considered thoroughly.

Appropriate intraoperative guiding methods are crucial for accurate transfer of the virtual surgical plan to the actual surgery. Surgical navigation is widely used in maxillofacial reconstruction surgery, with a reported deviation of less than 2 mm[12,18]. In this study, 60% of the maxillary defect restorations were guided by surgical navigation due to the relatively stable position of the maxilla and skull base. Computer-assisted fabricated individual titanium mesh and plates were also combined with surgical navigation to assist flap positioning and orbital reconstruction. With regard to post-traumatic mandibular defects accompanied by dislocation of the ramus, a 3D-printed resin surgical plate is preferred to assist ramus repositioning and to maintain the dimension of the defect.

There appears to be no similar study reporting the accuracy of post-traumatic reconstruction. In this study, the overall accuracy was found to be lower than those reported in previous studies that have focused on reconstruction after tumour resection, but it was still within the acceptable error margin. Two factors may have contributed to the lower accuracy: (1) patients in this study underwent simultaneous delayed fracture reduction and defect repair. However, other studies have focused on isolated fracture reduction or reconstruction. The complexity of the surgery determined the difficulty of realizing the virtual surgical plan. (2) This study included defects in different locations (maxilla, mandible, zygoma, frontal bone), but other studies have focused on only one type of defect. The varying types of defects also contributed to lower accuracy. Personal errors from the use of titanium mesh and the prefabricated titanium plate processes were also an inevitable factor.

The goal of post-traumatic bone defect restoration is to rehabilitate the aesthetic appearance and oral function with minimal additional trauma. Thus, minimally

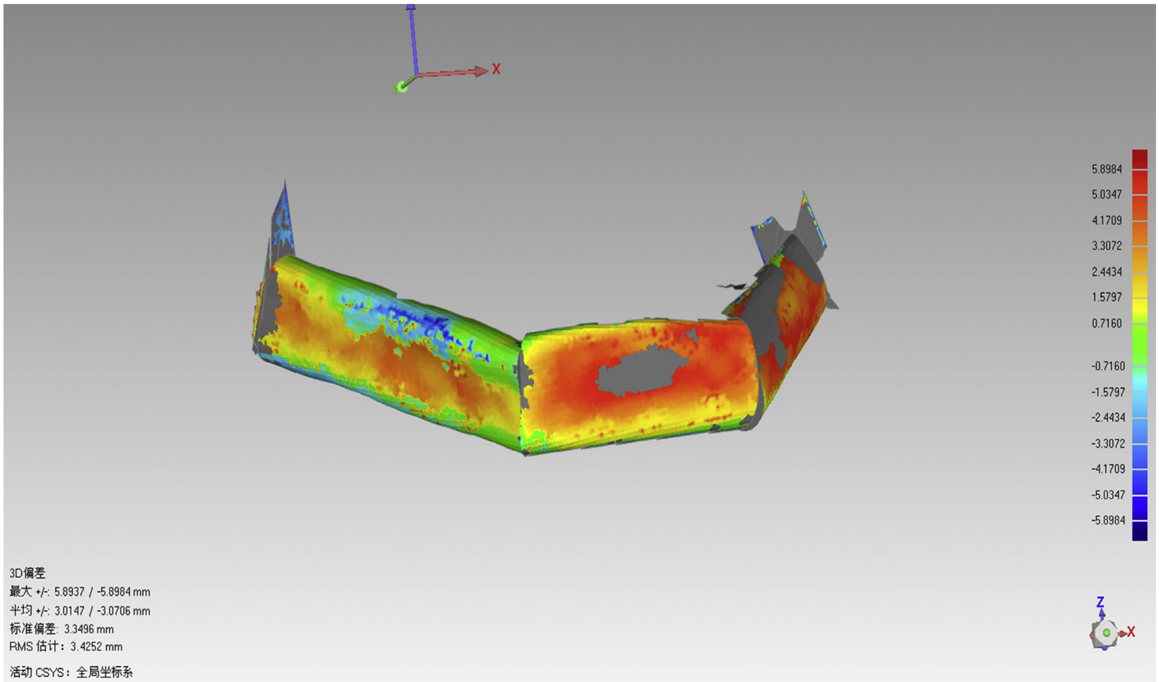

Fig. 5. Colour-graded error map generated by automatic registration and superimposition of the preoperative design and postoperative results. The green colour areas represent surface distance differences of less than 0.7 mm. The average deviation of this fibula reconstruction was 3.35 mm (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

invasive operation techniques should be taken into consideration. Compared with conventional anastomosis via submandibular skin incision, intraoral anastomosis and use of the superficial temporal vessels are the first choice for avoiding additional extraoral scars and postoperative immobilization. In this study, two patients with maxillary defects underwent reconstruction with a DCIA flap in which the superficial temporal vessels were used as recipient vessels. Anatomical studies on the superficial temporal vessels have shown that the mean diameter of the frontal branch is 2.14 ± 0.54 mm and of the parietal branch is 1.81 ± 0.45 mm[19], matching the diameter of the DCIA. With the development of surgical techniques, intraoral anastomosis was used in three cases in more recent years. Despite the difficulties in preparing the facial vessels, the intraoral anastomosis technique using the facial vessels and the transmucosal approach has proven to be a safe and minimally invasive approach for maxillofacial microvascular reconstruction[20,21].

Due to variations in the skin paddle and limitations of 3D simulation methods, the preoperative design of soft tissue reconstructions is currently impossible. For now, the soft tissue defect size can only be determined after fracture reduction. Given that post-traumatic bone defects are often accompanied by soft tissue defects, many patients receive secondary soft tissue revision procedures for malar prominence or plastic surgeries for restoring cosmetic organs. Future studies focusing on soft tissue prediction after bone defect repair should be conducted to improve the rehabilitation of the aesthetic appearance in trauma patients.

This study is novel in presenting a treatment protocol for post-traumatic maxillofacial bone defect repair with vascularized flaps assisted by digital techniques. This is a feasible method that enables individualized, minimally invasive, and functional reconstructions.

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Competing interests

All authors declare that they have no conflict of interest.

Ethical approval

The Ethics Committee of Peking University School and Hospital of Stomatology (PKUSSIRB-201949138) approved this study.

Patient consent

All participants signed an informed consent agreement.

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