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TECHNICAL NOTE

Assembly of 3D-printed Ti scaffold and free vascularized fibula using a customized Ti plate for the reconstruction of mandibular defects

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Introduction

Mandibular segmental defects result in significant cosmetic and functional deficiencies. Meanwhile, the reconstruction of both the contour and function of the mandible is a challenging task.

At present, autologous vascularized fibula transplantation is the most common method to reconstruct a mandible with long-span defects [1]. However, the fibular width usually mismatches the defect height and the discrepancy leads to the inability to consider both the rehabilitation of the mandibular inferior border and the reconstruction of the occlusal function [2]. Many experts use the "double-barrel" approach to address this problem, but this technique presents the following shortcomings: (1) As it increases the length of fibular flap and expands any damages, the mandibular defect should be within 10 cm in length [3]; (2) the height of folded fibula is too great to have a sufficient vertical distance for implant rehabilitation [1]; and (3) the shape of fibular flap mismatches the inferior border of mandible, leading to an inaccurate contour [4]. Therefore, it is of great clinical significance to find a solution for the reconstruction of both occlusal function and facial beauty.

Herein, we propose a new method to achieve occlusal reconstruction and accurate contour rehabilitation at the same time. The dental implant-oriented functional reconstruction is combined with the computer-aided design (CAD). It raises the fibular flap to shorten the vertical distance of the bite, so as to obtain a reasonable top root ratio of implant teeth, and the remaining defect of the mandibular inferior border is restored using a 3D-printed personalized titanium prosthesis (Fig. 1). The whole treatment process can simultaneously realize digital design, digital manufacturing, and digital surgery.

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Procedure

Technical key points

Design of the fibular flap position and osteotomy guide plates

The computed tomography (CT) data of patients were imported into Mimics 20.0 software (Materialise, Belgium) in DICOM format for the 3D reconstruction of jaw bones and fibula. The range of segmental mandibulectomy and the mandibular osteotomy guide plate was planned in this software. Previous studies showed that the necessary interarch distance to accommodate denture teeth is 25–28 mm for the anterior area and 20–22 mm for the posterior area [5], and the required gonial angle is about 125°. Based on the occlusion of remaining teeth, the number, sites, and directions of implant teeth were planned first. Then, considering the thickness of soft tissue in the operative area and bone resorption at the alveolar fracture margin, the position and splicing pattern of raised fibular flap were determined to obtain a suitable top root ratio of implant teeth. Finally, the fibular osteotomy guide plate was designed.

Design of the titanium plate

A personalized titanium plate with sufficient mechanical strength was designed to fix the fibular flap and undertake

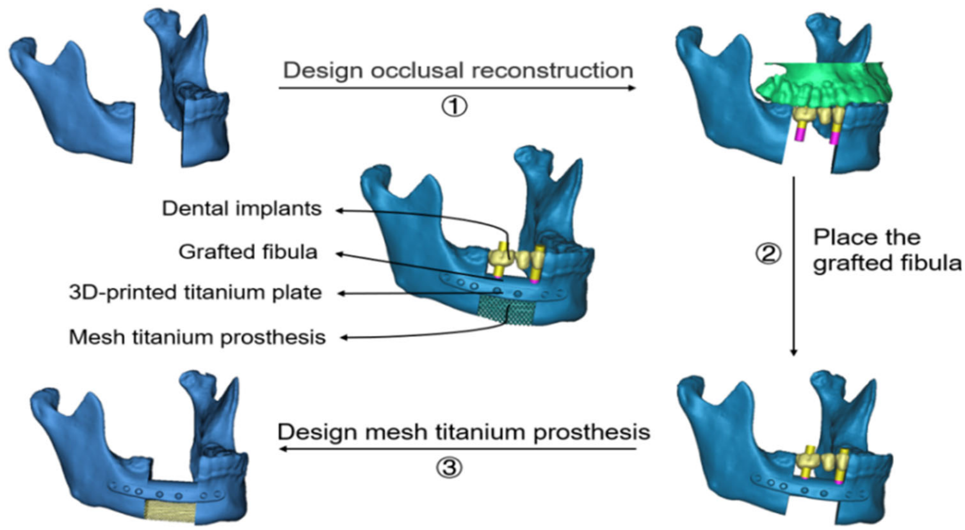

Fig. 1 Workflow of the proposed method for mandible reconstruction

forces. The reconstructed model was imported into 3-matic (version 10.2, Materialise, Belgium) in the Standard Template Library (STL) format. Referring to the commercial titanium plate (Tianjin Kanger Medical Treatment Apparatus Co., Ltd., China), the parameters of the personalized plate were 8 mm in width and 2.3 mm in thickness. Two to three retention screw holes on each fibula segment and 3–4 holes on each broken end of the mandible were reserved, and the distance between two adjacent holes exceeded 8 mm [6]. The hole position prevented interrupting the key anatomical structures and dental implants.

In order to test the mechanical strength of the titanium plate, the model was imported into Geomagic Wrap in STL format to realize substantiation, and the entity model was imported into Workbench (ANSYS Inc., USA) in the Initial Graphics Exchange Specification (IGES) format to perform finite element analysis. The material properties of related components are given in Table 1. The model was simulated under the assumptions of static load conditions. Six clenching tasks were performed as follows: incisal clench (INC), intercuspal position (ICP), right unilateral molar clench (RMOL), left unilateral molar clench (LMOL), right group function (RGF), and left group function (LGF). The simulative forces were derived from the bite force of remaining teeth and seven muscle forces, including superficial masseter (SM), deep masseter (DM), medial pterygoid (MP), inferior lateral pterygoid (ILP), anterior temporalis (AT), middle temporalis (MT), and posterior temporalis (PT). The values and directions of individual forces were based on the previous literature (Fig. 2a) [7–10]. The detailed data are given in Tables S1–S3.

Table 1 Material properties of the related components in finite element analysis

Material	Young's modulus (MPa)	Poisson's ratio
Cortical bone	13,700	0.3
Cancellous bone	1,850	0.3
Tooth	20,000	0.3
Titanium alloy (Ti-6Al-4 V)	113,800	0.342

According to the finite element analysis (Figs. 2b and 2c), the maximum von Mises stress of the reconstructed mandible, titanium plates, and screws was lower than their corresponding yield strength under all loading scenarios. The stress and deformation distribution were similar under the six conditions. The site with the most concentrated stress was the junction of the grafted fibula and the native mandible. The proximal end of the plate-screw system possessed the maximum deformation. The detailed data are presented in Figs. S1–S6.

Design of the titanium prosthesis

A personalized lightweight meshblock titanium prosthesis was designed below the fibular flap in Magics 24.0 software to rehabilitate the inferior border of mandible. The unit was a dodecahedron structure, and the single face was diamond-shaped with 1 mm side length. The prosthesis was based on the mirror image of the contralateral mandible. The Boolean operation made the upper surface of the prosthesis fit the inferior border of the fibular flap, while its lower surface was along the inferior border of the normal mandible. The thickness was designed to be 1/2–2/3 of the normal buccolingual thickness of the mandible, and the fullness of the mental region was restored. The two junctures of mandible and prosthesis performed a smooth transition to avoid stress concentration. Considering that the bite force was borne by

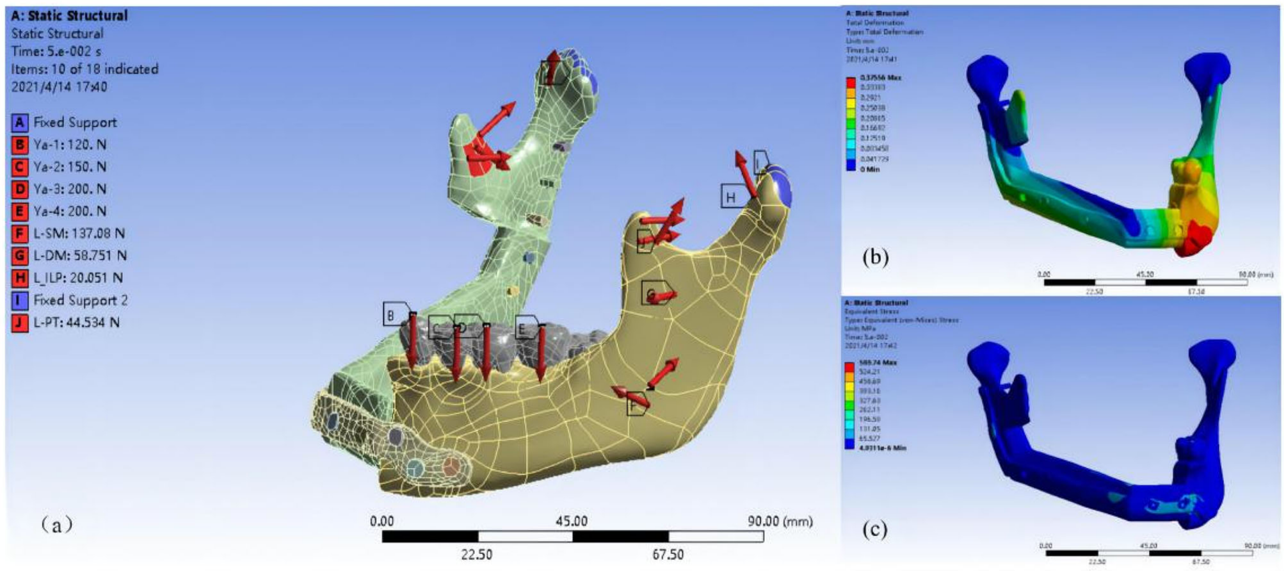

Fig. 2 Finite element analysis under LMOL: **a** directions of individual forces; **b** deformation of the model; **c** stress distribution of the model

the fibular flap and the titanium plate, only two upward screw holes were reserved at each end of the prosthesis.

The personalized titanium alloy plate and prosthesis were made of medical Grade 5 titanium powder (TC4) and formed by selective laser melting (SLM).

Case report

The patient was a 32-year-old female diagnosed with ameloblastoma. The CBCT (scan thickness of 0.3 mm) showed a large tumor (approximately 77 mm × 27 mm × 25 mm) extending from the affected gonial to the contralateral central incisor. The reconstruction surgery was performed adopting the proposed method. The tumor and tissue to about 10 mm beyond the invasion range were precisely removed [11]. The patient was a young female with high esthetic requirements; therefore, we modified the gonial position 5 mm forward, 3 mm upward, and 3 mm inward from the original position to avoid facial asymmetry caused by swelling (Fig. 3). The surgery process is presented in Fig. S7.

The postoperative monitoring demonstrated that the grafted fibular flap showed survival and the operation was uncomplicated. The patient obtained a good mandibular function and satisfactory facial profile (Fig. 4). The postoperative model was imported into Geomagic Wrap in STL format to perform the fitting analysis with the preoperative model. The results showed that the standard deviation of the whole mandible was 1.308 mm, the mean deviation was +1.0526 mm and −0.936 mm, the deviation of the gonial angle was 0.56°, the standard deviation of the condylar process was 1.231 mm, and the deviation of fibula osteotomy was 0.12–0.72 mm. These results were considered satisfactory. The detailed data are presented in Fig. S8, Fig. S9 and Table S4.

Discussion

This paper introduced a new strategy for the reconstruction of a mandible with severe segmental defects by combining customized 3D-printed titanium implants with autologous vascularized fibula transplantation. It was based on the dental implant-oriented elevation of the fibular flap and the digital design of osteotomy guide plates and titanium implants. In this manner, surgeons could rehabilitate the facial profile and reconstruct the occlusion function.

One of the distinctive features of this study was the dental implant-oriented elevation of the fibular flap. As opposed to previous methods, we firstly simulated the postoperative occlusion and then designed the position of fibular flap to obtain an appropriate top root ratio of implant teeth. Studies have shown that the average length and width of fibula in adults are (33.84 ± 2.68) cm and 1.31–1.71 cm, respectively, and its thickness is about 1.5 cm [12]. Meanwhile, the mandibular body is (10.36 ± 0.79) cm long and (3.09 ± 0.26) cm high in men, while it is (9.25 ± 0.58) cm long and (2.83 ± 0.24) cm high in women; the height of the mandibular ramus is (6.41 ± 0.56) cm in men, while it is (6.16 ± 0.44) cm in women [13]. It should hold at least 5 cm and 8 cm long at the proximal and the distal end of fibula, respectively, to maintain the joint's stability [3]. The available length of fibula, which can meet the needs of long-span mandibular defects, is therefore

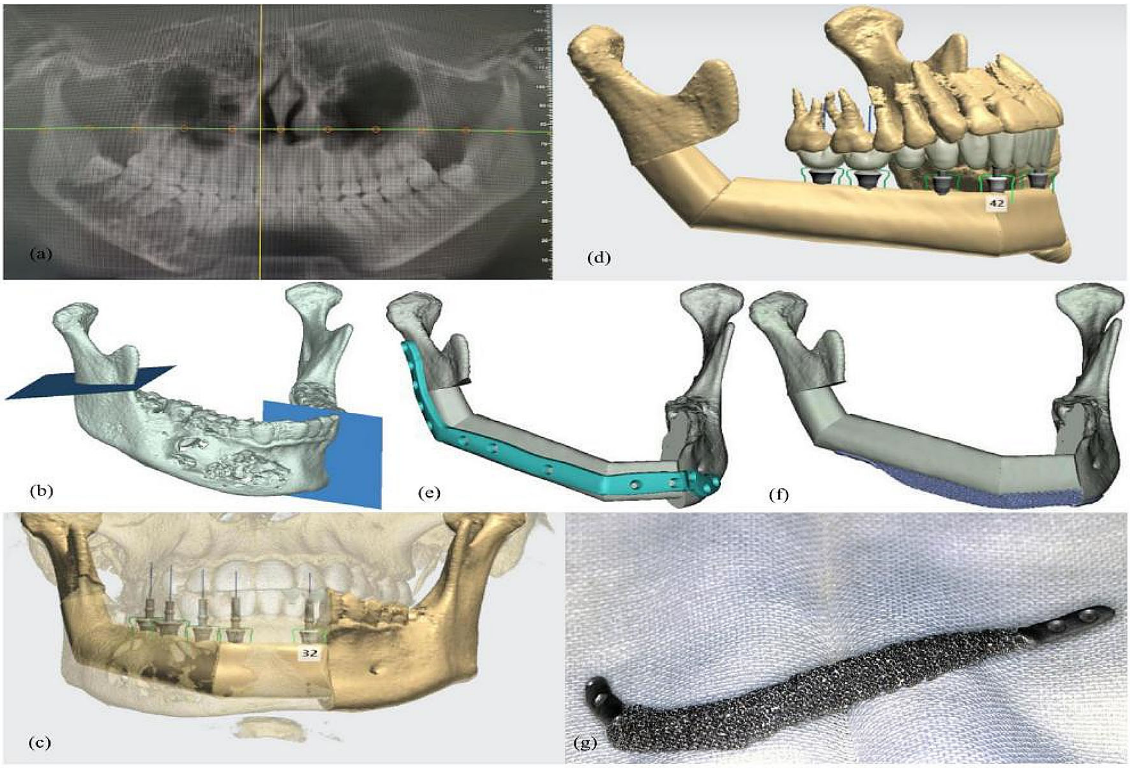

Fig. 3 Preoperative plan: **a** CBCT image of the mandible and the tumor; **b** simulative resection range of the lesion on the 3D model; **c**, **d** simulative position of implant teeth and raised fibular flap; **e** designed titanium reconstruction plate; **f** model of 3D-printed personalized mesh titanium prosthesis; **g** entity of 3D-printed personalized mesh titanium prosthesis

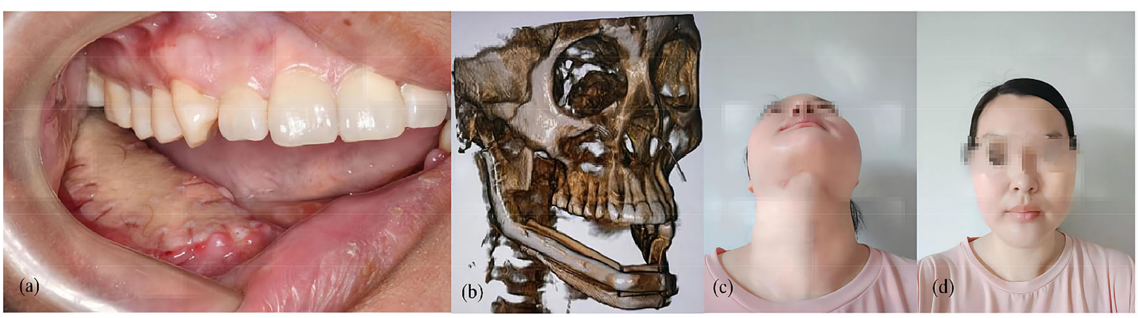

Fig. 4 Postoperative information: **a** satisfactory soft tissue healing and blood supply 3 days after operation; **b** CBCT 3D image 3 days after operation; **c** facial profile was almost symmetrical 2 months after operation; **d** wound healed well 2 months after the operation

(22.2 ± 2.5) cm. Due to the height mismatch between the fibula and the mandibular body, it cannot repair the contour of the mandibular inferior border and meet an appropriate vertical distance for secondary occlusal reconstruction at the same time. When using the double-barrel technology, for patients with a lower height of the mandibular body, especially those with severe alveolar bone resorption, the folded fibular flap is too high to achieve a sufficient vertical distance [14]. This method also faces the challenges of difficult bone shaping, complex microvascular anastomosis, long operation time, and increased trauma [15]. However, the approach proposed in this paper provides more convenience.

Another feature of our method is the customized 3D-printed digital design. The osteotomy guide plates, the position and the splicing pattern of raised fibular flap, and the titanium implants were designed on 3D models and were fabricated by SLM. Studies proved that annealing and SLM provide the best physicochemical characteristics when preparing a personalized titanium implant [16]. In light of the finite element analysis results, the titanium plate-screw fixation system presented a better stability and safety as compared to the conventional technique, with an inappreciable possibility of fracture. Studies showed that the effective strain range of bone graft to promote bone remodeling was 50–3000 με [17]. Thus, no obvious stress shielding or overload was present in this system, and the grafted fibula could remodel normally. The deformations of native mandible during clenching tasks ranged from 0.46 to 1.06 mm [7]. Therefore, except for the LMOL condition that was merely within this range, others were lower. This finding indicated that the rigid titanium plate-screw fixation system possessed a preliminary stability [10]. Due to the deformation at the proximal end of the system, the screws may face loosening and exfoliation. Compared with the commercial titanium plate, the 3D-printed one needed no repeated bending, and it reduced operation time and technical difficulty. It also fitted the bone surface more accurately and decreased the risk of fatigue fracture, corrosion, screw loosening, and bone resorption [18]. Based on the lightweight design, the prosthesis with a porous structure rather than a solid one was used to facilitate tissue growth and reduce the risk of necrosis, infection, and implant exposure [19]. Moreover, it had little effect on osseointegration. The titanium plate either remained for a long time or was removed by secondary surgery according to the patient's decision. Meanwhile, the prosthesis needed to be retained for a long time to maintain the facial profile.

Some scholars have pointed out that reconstruction surgery with simultaneous implant rehabilitation may lead to inadequate bone mass surrounding the dental implants and gaps between the mandible and the fibular flap. In addition, this method may cause peri-implant inflammation resulting in poor initial stability and the loosening of dental implants. It is easy indeed to increase the risk of postoperative vascular crisis [20]. Therefore, the secondary implant rehabilitation was deemed optimal when the fibular flap presented a preliminary osseointegration with the native mandible.

Using this method, we could perform the mandible reconstruction to match the design criteria: safety, functionality, and esthetics. Its short-term impacts were stable, while evaluating the effects after implant rehabilitation still needs further follow-up. Nonetheless, combining tissue engineering with 3D printing to achieve bone regeneration is still regarded as a feasible direction of our efforts, as the presented method has been a huge leap in our ongoing struggle to provide new ideas for the reconstruction of severe mandibular defects.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42242-021-00181-0.

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Author contributions All authors contributed to the study design. Material preparation, data collection, and analysis were performed by CYZ, YXZ, HYX, QGL, RQX, TXS, XPT, KWZ, and YWD. The first draft was written by CYZ and YXZ. All authors read and approved the final manuscript.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval This study was approved by the Ethics Committee of the Second Hospital of Shandong University and was carried out in accordance with the Helsinki Declaration of 1975, as revised in 2000 (5). Informed consent was obtained from all patients. Clinical Trial Number: 2020SDUCRCB001. WHO ICTRP Number: ChiCTR2000038973. Ethical Approval Number: KYLL-2020(KJ)P-0157; LCLL-2020-006.

Data and materials availability Any data used to support the findings of this study were included within the article.

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