The Precision of Different Types of Plates Fabricated With a Computer-Aided Design and Manufacturing System in Mandibular Reconstruction With Fibular-Free Flaps

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Abstract: Computer-assisted surgery (CAS) has been introduced to mandible reconstruction with fibular-free flap in cutting guide placement. When CAS cooperates with different plate fixations, the results show various degrees of errors by which this study aimed to evaluate. Mock surgeries were conducted in 3D-printed mandibles with 2 types of defects, limited or extensive, reconstructed from 2 ameloblastoma patients. Three types of fixations, miniplate, manually bending reconstruction plate, and patient-specific plate, are tested, each of which was performed 3 times in each type of defect, adding up to 18 surgeries. One with the least errors was selected and applied to patients whose 3D-printed mandibles were derived. Finally, in vivo errors were compared with the mock. In limited defect, average errors show no statistical significance among all types. In extensive defect, patient-specific plate had a significantly lower average condylar error than manually bending reconstruction plate and miniplate (8.09 ± 2.52 mm vs. 25.49 ± 2.72 and 23.13 ± 13.54 mm, respectively). When patient-specific plate was applied in vivo, the errors were not significantly different from the mock. Patient-specific plates that cooperated with CAS showed the least errors. Nevertheless, manually bent reconstruction plates and miniplates could be applied in limited defects with caution.

Key Words: computer-assisted surgery, mandibular reconstruction, fibular-free flap

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Computer-assisted surgery (CAS) has been used for head and neck surgery, including fibular free flap surgery, since the 1990s1–3 and is widely used even today.1 In practice, CAS consists of 2 components: computer-aided design (CAD) and computer-assisted manufacturing (CAM).2,3 CAD/CAM and the cutting guide increase the accuracy of fibular free flap surgery,4–6 decrease the operative time,1,3 decrease ischemic time,4 and are easy to use.5 Furthermore, the increase in accuracy contributes directly to the esthetic results and functional outcomes related to the position of the mandibular condyle and temporomandibular joint (TMJ).5,6

The cutting guide transfers a mock-up to the surgical field. If the cutting guide is accurately positioned on the patient, the accuracy of other aspects of the guide will also be achieved. A recent study by Yang et al7 found that the use of CAS combined with a patient-specific plate, specifically a 3D-printed customized mandibular reconstruction plate, in nonextensive defects increases the spatial accuracy of the TMJ reconstruction, yielding better results than commercially available manually bending reconstruction plate. Even though the patient-specific plate can provide good results, surgeons may adopt different methods for bone fixation processes, such as miniplate and manually bending reconstruction plate. This indicates that most surgeons can access CAD/CAM for preparation for surgical planning and cutting guides. Nevertheless, it is challenging to obtain patient-specific plate. Currently, there is no research on the precision of using cutting guides with different fixation methods.

Therefore, in mandibular bone models, we investigated the errors of different fixation methods and the extent of defects in fibular free flap surgery using CAD/CAM and cutting guides. The 3 objectives of this study were to (1) compare the errors in the mandibular condyle and the fibular model among different types of fixation, (2) compare the errors associated with the defect extent and type of fixation, and (3) evaluate the underlying causes of the aforementioned errors.

MATERIALS AND METHODS

This study was approved by the Institutional Review Board (IRB) of the Faculty of Medicine Siriraj Hospital (Approval no. 369/2563). All methods were performed in accordance with the relevant guidelines and regulations, including the Declaration of Helsinki. 

The authors declare no conflict of interests.

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of Helsinki. The informed consent was obtained from all subjects and/or their legal guardian(s). The prototypes of the mandible models were retrieved from 2 patients with ameloblastoma who had different defect characteristics. The “limit defect” involved the parasymphysis of the mandible to the ipsilateral angle of the mandible and required reconstruction with 2 segments of the fibula. The “extensive defect” involved the body of the mandible to the contralateral angle of the mandible and required 3 fibular segments for reconstruction (Fig. 1). Both defect types were classified as class I and II in Marchetti and Tarasitano, respectively. By the means of using fibular segmentation for reconstruction, both types of defects resembled other defect types in general.

This study was conducted in 2 parts: one was a surgical simulation in bone models, and another was mandible reconstruction with patient-specific plate in vivo. In the first part, which was our primary consideration, we performed 18 mock-up surgeries in the bone models in total. The models were divided into 2 groups according to the extent of the defect. Bone fixation was performed with 3 types of plate, miniplate, manually bending reconstruction plate, and patient-specific plate. All model experiments were done with each type of plate 3 times, and the results were averaged (Fig. 2). In the second part, we studied the accuracy of actual fixation with patient-specific plate in vivo in 2 patients who were used as the reference for the bone model surgery.

**Mandibular and Fibular Model Preparation**

Two ameloblastoma patients underwent computed tomography (CT) scans on a GE revolution system (GE Healthcare, Chicago, IL), with a 0.625 mm thickness for the facial bone and 1.25 mm thickness for the lower extremity, with intravenously administered iodinated contrast medium (Iopamiro370, Bracco, Israel). Subsequently, the data, in the form of a Digital Imaging and Communications in Medicine file, was transformed into 3D models of the fibula and the mandible in the form of a stereolithography interface file using Avizo software (Thermo Fisher Scientific Inc, Waltham, MA). Segmentation of bone was applied based on a value of 250 to 2500 Hounsfld unit, which was described as the standard reference value among studies.

**Virtual Surgical Planning and Surgical Guide Model Preparation**

The surgeon determined the cutting position on the mandibular model. Then, the engineering team designed cutting guides for the mandible and fibula and patient-specific plate with Ansys Space Claim software (Ansys Inc, Canonsburg, PA). The screw drilling positions for patient-specific plate were also indicated preoperatively.

**Bone Model and Surgical Guide Manufacturing**

The bone models and cutting guides in this study are made of polyamide thermoplastic. Each set of synthetic bone models consisted of a mandible and fibula. Eighteen sets of models were used in this study. These models were manufactured with fused deposition modelling technology using a Zortrax M300 (Zortrax, Poland) FDM 3D printer. The model is printed in layers using a single 0.4 mm nozzle print head where the filament is melted at a temperature ~50% higher than the material’s melting temperature. The printed pattern of the bone model is a honeycomb lattice infill.

This experiment is established to specifically confirm whether infill density really affects the screw deviation. The experiment separates into 2 groups, the high-density infill of the bone model (70% infill) with 3 samples and the low-density infill of the bone model (30% infill). The result shows that there are no significant differences in screw deviation between the 2 groups. The mandibular and fibular surgical guides were manufactured with the same process.

**Plate Preparation Method**

We prepared 3 different types of fixation systems: a 2.0 mm titanium miniplate (Leibinger Universal CMF Plating System, Stryker, MI), a 2.3 mm titanium manually bending reconstruction plate (KLS Martin, Tuttingen, Germany) and a patient-specific plate (Meticuly Co Ltd, Bangkok, Thailand). The manually bending reconstruction plate was prebent with a printed reconstructed mandibular model. The patient-specific plate was manufactured with selective melting technology (Mlab cusing 200R, GE Additive, Lichtenfels, Germany) with medical-grade Ti-6Al-4 V alloy (Rematitan CL, GE Additive, Lichtenfels, Germany).

**Surgical Simulation in the Bone Model**

The simulation of mandibular reconstruction with a fibular-free flap was carried out using bone models. All surgical simulations were performed by the senior author (N.Y.). First, the mandibular and fibular cutting guide was applied to the bone model. Then predrilling and screwing were implemented to define the screw positioning for the cutting guide and plate fixation. After the cutting guide was attached by screws, the bone model was cut with an electrical bone saw using the 1-mm thickness saw blade (Primado2, NSK, Kanuma, Tochigi, Japan). The plastic cutting guide was covered by the metallic sleeve to avoid cut through the plastic cutting guide. After the mandibular defect was created and the artificial fibula parts were made, each part of the fibula was attached to the defect using different types of plate according to the protocol. Then, all the simulation models and fixation parts underwent CT scanning.
The metallic artifact from plates and screws were evaluated in CT, however, such artifacts did not clinically affect the segmentation and contouring of bone.

**Mandibular Reconstruction in vivo**

The 2 aforementioned ameloblastoma patients underwent mandibular reconstruction after tumor eradication with fibular-free flaps using CAD/CAM cutting guides and patient-specific plates. The operative steps were similar to those used in the surgical simulation of bone models. All fibular-free flaps were viable, and no postoperative complications occurred. After 1 year of surgery, both patients underwent follow-up CT scans, the fibular-free flaps were properly healed, and no late complications were observed.

**Superimposition of Reconstructed Mandible Model**

We converted the postoperative CT scan images from the Digital Imaging and Communications in Medicine format to the stereolithography interface format. Each part of the reconstructed model was independently segmented and then superimposed on the preoperative mandible. The superimposition involved a semi-automatic registration process using 2 algorithms for surface alignment and few manual adjustments.

A manual adjustment is adopted at the beginning of the process to translate the preoperative model from the origin to the position of postoperative segmented model. However, it could not provide the best superimposition between the 2 models. Accordingly, it requires a surface alignment algorithm for better overlaying on postoperative segmented model.

To confirm the superimposition, the surface distance algorithm is employed to measure the distance shift between models with color and numerical visualization.

We set the large side of the remaining mandible, which was the left side for both types of defects in this study, as the reference for superimposition. There were 5 main reference points on the mandible. To ensure the correct positioning of the superimposition, the 5 main reference points had to have an error less than 1 mm between the preoperative and reconstructed images (Fig. 3).

**Measurement, Analysis of the Results and Statistical Analysis**

The errors between the preoperative and postoperative surgical simulations in bone models are presented as the mean and SD. The errors among the types of plate and the extent of defects were also compared. Finally, we compared the error between surgical simulation in bone model and actual mandible reconstruction in vivo.

We also analyzed the cause of error using numerical data and analyzed 3D model images to determine the position of the screw hole at the surface of the bone model and the direction of

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**FIGURE 2.** The allocation of bone model experiments among defect types and mandibular plates. Each type of defect was fixed with different types of plate, including miniplate, bendable reconstruction plate, and patient-specific plate. All models were fixed with each type of plate 3 times, and the results were averaged.
the screw tract within the bone model. This measurement relied on the hypothesis that the screw position and tract reflect the precision of the cutting guide position and the outcomes of the surgery.

Data analyses were conducted using IBM SPSS Statistics, version 22.0 (IBM Corp., Armonk, NY). We tested the normality of the data using the Shapiro–Wilk test. If the data had a normal distribution, the accuracy was determined by the independent t test or analysis of variance. Kruskal–Wallis test or independent-samples Mann–Whitney U test was used for nonnormally distributed data. A P-value less than 0.05 was considered statistically significant.

RESULTS

The experiment was conducted on 18 bone models and 2 actual patients whose data had been used to construct the bone models.

Effect of Plate Type for a Limit Defect and Extensive Defect

The errors from the 3 types of plate are shown in Figure 4. For the limit defect, both the average fibular and average condylar errors were not significantly different among plate types. The average condylar errors of patient-specific plate (7.53 ± 2.75 mm) and manually bending reconstruction plate (5.51 ± 1.59 mm) were lower than those of the miniplate (17.64 ± 10.29 mm) for the limit defect.

For the extensive defect, patient-specific plate had the lowest error for the condylar position (7.50 ± 2.48 mm), being significantly lower than those of the manually bending reconstruction plate (25.49 ± 2.72 mm) and miniplate (23.13 ± 13.54 mm). There were no significant differences in error between manually bending reconstruction plate and miniplate. Regarding fibular errors, it was found that the group that underwent fixation using patient-specific plate had lower errors than those that underwent fixation using a manually bending reconstruction plate and miniplate, which was the same trend as that for condylar errors, but the trend was not statistically significant.

The average condylar errors for the limit defect were smaller than those for the extensive defect in all plate types. Furthermore, the manually bending reconstruction plate had significantly smaller errors (P < 0.01). The average fibular errors for the limit defect were smaller than those of the extensive defect for all plate types. Miniplate and manually bending reconstruction plate had significantly different errors. The overall precision of patient-specific plate was comparable in both condylar and fibular errors for all axes, and statistical analysis showed no significant difference associated with defect extent (P > 0.05).

Individual analysis of each plate found that the patient-specific plate had the lowest fibular and condylar errors on the x-axis (medial-lateral direction). This trend was the same for both the limit and extensive defects. The largest errors were found on the y-axis (superior-inferior direction) for all experimental models. The average errors of the patient-specific plate in both the limit and extensive defects had comparable values, which indicated the benefits of the patient-specific plate regardless of defect extent (Fig. 5).

For the manually bending reconstruction plate, it was found that the fibular and condylar errors occurring in the z-axis (anterior-posterior direction) were the lowest for the limit defect. Each model in the experiment had a different twisting angle, and the errors could occur on any axis (Figs. 5 and 6).

A comparison of errors according to the size of the defect found that when the defect was broad, there were significantly more errors on the z-axis ([anterior-posterior direction] (0.99 ± 0.93 mm vs. 5.30 ± 2.70 mm for the limit and extensive defect, respectively]).

For miniplate fixation, the maximal condylar errors were found on the x-axis (medial-lateral direction) for both the limit and extensive defects. As a result, the mandible widened. There was no statistically significant difference in average errors according to the extent of the defect. There were higher fibular and condylar errors on the z-axis (superior-inferior direction) for the extensive defect group but were not statistically significant (Fig. 5).

Analysis of Screw Holes Position

The locations of the screw holes were used as an indicator of the accuracy of cutting guide placement. The locations of the screw holes at the bone surface were accurate for both extents of the defect, with errors of less than 1 mm in all directions. There was no significant difference in the average error according to the extent of the defect (Fig. 7).

Analysis of Screw Direction

When the screw passes through the material, it can change direction towards any axes away from the predrilled hole. For the patient-specific plate, the screw deviated from the predrilled hole to the y-axis (superior-inferior direction) in all experimental models (Fig. 8). Thus, the direction of the screw, especially near the cutting surface, indicated the axis deviation of the plate. Moreover, it was found that the degree of fibular bone error was proportional to the magnitude of the screw deviation.

For the manually bending reconstruction plate, the screw also changed direction of the y-axis (superior-inferior direction), similar to the patient-specific plate, and it was found that the fibula rotated around both the x-axis (medial-lateral direction) and y-axis (superior-inferior direction) in each bone model. The errors in the screw direction were insignificant for all axes for the miniplate.
Comparison of Simulation Bone Model and Reconstructed Mandible in vivo

The errors between the actual reconstructed mandible in vivo using the patient-specific plate and surgical simulation of the bone model were compared. The errors were lower for the actual reconstructed mandible in vivo for all plate types and defect extents. For the limit defect, it was found that the fibular and condylar errors in the actual reconstructed mandible in vivo and surgical simulation of the bone model were $1.30 \pm 0.27$ mm versus $5.07 \pm 2.7$ mm and $0.67 \pm 0.00$ mm versus $16.15 \pm 3.49$ mm, respectively (Fig. 9).

For the extensive defect, it was found that the fibular and condylar errors for the actual reconstructed mandible in vivo and the surgical simulation of bone models were $4.78 \pm 1.14$ mm versus $5.07 \pm 2.7$ mm and $1.80 \pm 0.00$ mm versus $8.09 \pm 2.52$, respectively.

The fibular errors for the surgical simulation of bone models and the actual reconstructed mandible in vivo were higher than the condylar errors for both the extent of defects but were not significant. The average condylar errors of the actual reconstructed mandible in vivo were lower than that in the surgical simulation of bone models, and this finding occurred for all axes of measurement. Furthermore, the errors that were found frequently in the bone model on the y-axis (superior-inferior direction) did not have a high value in the actual reconstructed mandible in vivo.

DISCUSSION

CAS in mandibular reconstruction with fibular-free flaps has become a new standard in medical treatment. A recent systematic review and meta-analysis showed various benefits, such as increased precision and accuracy in reconstruction, decreased operative time, and increased long-term stability.

In general, it was found that CAS for fibular-free flaps can be divided into 2 parts. The first part is for surgical planning and creating cutting guides to assist in the surgery. The second part...
involves mandibular plate preparation for the fixation. It is vital to position the planned plate and bone graft to the surgical site with precision. Guides serve as the essential link between virtual planning and surgery. Moreover, guide design and precision are key to bringing a reconstruction plan to reality. In accordance with Marchetti and Tarsitano's study, the fibular-free flaps were favored because the fibula was very adaptable and produced the longest bony flap. Reconstruction of advanced mandibular defects (Classes II and III) typically involves the use of multiple fibular segments (2.9-4.3) obtained with the use of cutting guides.

FIGURE 5. Comparison of error between defect extent groups by plate type. (A,B) The patient-specific plate had comparable condylar and fibular errors regardless of the defect extent. The extent of the mandible defect had less effect on patient-specific plate error. (C,D) The manually bending reconstruction plate can have an error for any axis, and there was a significant difference in average errors between the limit and extensive defect groups. (E,F) For miniplate, the average errors were generally higher than those for other plate types, and the average errors were higher in the extensive defect group but not statistically significant.
According to published literature, the subjects were separated into 3 categories by using different plate fixation methods. The first group used CAD/CAM combined with patient-specific plate.15–17 The second group used CAD/CAM combined with manually bending reconstruction plate.4,5,18–26 The last group used CAD/CAM combined with miniplate.27,28

The factors affecting the selection of fixation plates are the availability of equipment, urgency of the operation, surgical planning preparation time, 3D printing process, CAD/CAM equipment transportation time, and expenses. Moreover, CAD/CAM technology has limited availability; only special laboratories in some hospitals have this service. So, the patient-specific plate is not always available for use in mandibular reconstruction. For alternative ways to the aforementioned issue, the authors aimed to determine which plate fixation technique is suitable and assists the reconstruction of the mandible with fibular-free flaps.

**Patient-specific Plate**

Regarding patient-specific plates, we hypothesized that the cutting guide determines the accuracy of the mandibular reconstruction by affecting the positioning of screws. The condylar errors were greatest on the y-axis (superior-inferior direction). After we analyzed the position of the screws on the bone surface, it was found that there was only a petite error (0.56 ± 0.38 mm) that was not proportionate to the condylar error (8.09 ± 2.52 mm), which was 14 times greater. Therefore, an in-depth analysis of the screw's direction was conducted. Apart from the screw position at the bone surface, the errors of screw direction inside the bone were high on the y-axis (superior-inferior direction) and directly resulted in the condylar error. The average errors of screw hole position at the bone surface were not significantly different regarding the extent of the defect, which indicated the accuracy of the screw hole direction at the point of entrance. The screws located near osteotomy sites affected the condylar errors for both direction and magnitude. Screw direction shifting was also found with the manually bending reconstruction plate. The manually bending reconstruction plate has a relatively large screw size compared with other plate types, resulting in a deviation of the screw from the predrilled axis. The finding supporting this hypothesis was that no significant error was found for fixation with miniplate, which uses smaller screws. In contrast, the smallest error on the x-axis (medial-lateral direction) could be explained by the supporting forces from surrounding soft tissue and TMJ on both sides of the mandibular condyle.

Therefore, to reduce error on the y-axis (superior-inferior direction), the cutting guide must be meticulously assembled and applied, and the screws must be installed precisely in all axes through the predrilled tract.

According to the results of the current study, patient-specific plate does not have significant benefits over manually bending reconstruction plate in terms of accuracy in the limit defect. This may be due to the ability of surgeons to bend the commercially available manually bending reconstruction plate for short and uncomplicated defects using hands and eyes. However, the surgeons' hand skills cannot overcome the challenge of extensive defects in the mandible, as we will describe in the next section.

**Manually Bending Reconstruction Plate**

The error of the manually bending reconstruction plate was highest on the z-axis (antero-posterior direction). We believe that this error occurred from the difficulty of plate bending, which was impeded by plate thickness. Surgeons can use the bone model of the mandible or the native mandible as a reference. The
main bending points are usually the points that can be clearly seen, such as the seam between the anterior and lateral part of the mandible, by bending the plate at significant points, which normally have 1 to 3 angles. However, in reality, the mandible is gradually curving and changes direction for 2 or more axes along its part. The limitation of manually bending resulted in the inadequate alignment between the plate and bone surface.

Furthermore, tipping and ejection of the plate on another end of the plate occurred after 1 distal end was fixed. The shifting of the plate in the antero-posterior axis (z-axis) might occur from a fixation force that tries to align the plate on the mandible, and there is room for the plate in this direction only (Fig. 10).

The patient-specific plate has not only great accuracy but also durability to force load. There was an in vitro study by Kasper et al., which reported that patient-specific plate seemed to benefit from manually bending reconstruction plate in terms of durability against physiological force loading. These results suggested the benefit of using patient-specific plate over manually bending reconstruction plate.

**Miniplate**

Most of the published literature focused on the stability of fixation and postoperative complications between using a miniplate and manually bending reconstruction plate. The difference in complications between these 2 plates remained controversial. A finite element study showed better stability in manually bending reconstruction plates over miniplate. Despite this question being critical, the data regarding the accuracy of miniplate fixation were limited.

In our recent study, it was found that using miniplate could create a condylar error on any axis. The leading cause of this error might occur from the uncontrollable overall shape of neo-mandible upon miniplate fixation. The aforementioned error was solved by using a “bar” to connect between both sides of the cutting guide, resulting in regulation of shape of the fibular segment and miniplate complex. Nevertheless, there were factors involving errors of fixation, not only of the bone, cutting guide, and plate complex, but also the forces from surrounding soft tissues, which distorted the plate and neo-mandible system postoperatively. Up to the present date, the studies on long-term outcomes of miniplate fixation are limited. Therefore, as the current evidence suggests, we do not recommend miniplate fixation in the first place. The summary of the errors in each plate type and recommendations are given in Supplemental Table 1, Supplemental Digital Content 1, http://links.lww.com/SCS/E552.

**Clinical Case Analysis**

From the analysis of errors in the actual reconstructed mandible in vivo, there were lesser errors than the surgical simulation in the bone model. Several hypotheses have been proposed for this manifestation. First, the bone model has a different internal supporting structure from human bone, which might cause different errors. In this regard, the surgeon may need to avoid forceful drilling when using relatively large screws, which are compatible with some types of plate, in patients who are fragile and/or have low bone density, such as elderly patients and those with osteoporosis. Furthermore, screws should be gently inserted along the predrilled axis to avoid false tract creation. Second, as mentioned above, in the
actual patient, both surrounding soft tissues and TMJs serve as support structures and guides for plate position in a functional position.

In the comparison of errors, the fibular error was greater than the mandibular error since the 2 errors in fixation occur first with the mandibular screw and second with the fibular screw. Hence, screw application and plate fixation should be performed meticulously to reduce this error.

Gravvanis et al. recommended reattaching the masseter muscle to the neo-mandible to help reduce the patient’s recovery time. On the other hand, this small error may not affect the patient’s functional outcome, and one could question the value of the investment, in terms of cost and time, in CAD/CAM and patient-specific plate. For example, the issue of minimal clinically important differences in mandibular reconstruction remains a question that requires further study.

**Limitations of the Study**

In this study, a few limitations should be considered when interpreting the experimental results. First, the sample size was relatively small among the published literature. Second, there were differences between the surgical simulation in bone models and actual reconstructed mandible in vivo, such as the screw direction errors, as detected in this study. In this case, we needed to consider the potential errors in the bone model itself. Furthermore, we should reconsider the interpretation of the results of previous studies conducted in models and those in future studies.

**CONCLUSIONS**

Despite using CAS combined with a cutting guide, errors still occurred, though they varied among plate fixation types. However, CAS combined with patient-specific plate had significantly smaller errors for both extents of the defect. Furthermore, this study showed that CAD/CAM, in combination with patient-specific plate, has benefits over other types of plate fixation in extensive defects as it reduces the condylar error, which other plate fixation methods cannot achieve. Interestingly, the errors of the patient-specific plate from the actual reconstructed mandible in vivo were lower in terms of both fibular and condylar errors, which might occur from the compensation forces of surrounding structures. Each plate type has...
limitations and errors, and surgeons should be aware of these issues. In conclusion, this study might support and ignite further clinical studies on the accuracy of mandible reconstruction in various aspects.

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REFERENCES

1. Hanasono MM, Skoracki RJ. Computer-assisted design and rapid prototype modeling in microvascular mandible reconstruction. Laryngoscope 2013;123:597–604
2. Ciocca L, Mazzoni S, Fantini M, et al. CAD/CAM guided secondary mandibular reconstruction of a discontinuity defect after ablative cancer surgery. J Cranio-maxillofac Surg 2012;40: e511–e515
3. Rodby KA, Turin S, Jacobs RJ, et al. Advances in oncologic head and neck reconstruction: systematic review and future considerations of virtual surgical planning and computer aided design/computer aided modeling. J Plast Reconstr Aesthet Surg 2014;67:1171–1185
4. Roser SM, Ramachandra S, Blair H, et al. The accuracy of virtual surgical planning in free fibula mandibular reconstruction: comparison of planned and final results. J Oral Maxillofac Surg 2010;68:2824–2832
5. Lethaus B, Poort L, Bockmann R, et al. Additive manufacturing for microvascular reconstruction of the mandible in 20 patients. J Cranio-maxillofac Surg 2012;40:43–46
6. Zavattiero E, Bolzoni A, Dell’Aversana G, et al. Accuracy of fibula reconstruction using patient-specific Cad/Cam Plates: A multicenter study on 47 patients. Laryngoscope 2021;131:E2169–E2175
7. Wang L, Liu K, Shao Z, et al. Management of the condyle following the resection of tumours of the mandible. Int J Oral Maxillofac Surg 2017;46:1252–1256
8. Nahe breadian MY, Tufaro A, Martin PN. Improved mandible function after hemimandibul ectomy, condylar head preservation, and vascularized fibular reconstruction. Ann Plast Surg 2001;46:506–510
9. Yang WF, Choi WS, Zhu WY, et al. Spatial deviations of the temporomandibular joint after oncological mandibular reconstruction. Int J Oral Maxillofac Surg 2022;51:44–53
10. Tarrazano A, Del Corso G, Ciocca L, et al. Mandibular reconstructions using computer-aided design/computer-aided manufacturing: A systematic review of a defect-based reconstructive algorithm. J Cranio-Maxillo Surg 2015;43:1785–1791
11. Akiyama K, Sakai T, Koyanagi J, et al. Three-dimensional distribution of articular cartilage thickness in the elderly cadaveric acetabulum: a new method using three-dimensional digitizer and CT. Osteoarthritis Cartilage 2010;18:795–802
12. Losch A, Eckstein F, Haubner M, et al. A non-invasive technique for 3-dimensional assessment of articular cartilage thickness based on MRI. Part 1: Development of a computational method. Magn Reson Imaging 1997;15:795–804
13. Yeung C, Deluce S, Willing R, et al. Regional variations in cartilage thickness of the radial head: Implications for prosthesis design. J Hand Surg Am 2015;40:2364–71, e1
14. Brown JS, Lowe D, Kanatas A, et al. Mandibular reconstruction with vascularised bone flaps: a systematic review over 25 years. Br J Oral Maxillofac Surg 2017;55:113–126
15. Zeller AN, Neuhaus MT, Weissbach LVM, et al. Patient-Specific mandibular reconstruction plates increase accuracy and long-term stability in immediate alloplastic reconstruction of segmental mandibular defects. J Maxillofac Oral Surg 2020;19:609–615
16. Sweed AH, Bolzoni AR, Kadubiec A, et al. Factors influencing CAD/CAM accuracy in fibula free flap mandibular reconstruction. Acta Otorhinolaryngol Ital 2020;40:138–143
17. Kasper R, Winter K, Pietzka S, et al. Biomechanical In vitro study on the stability of patient-specific CADCAM mandibular reconstruction plates: A comparison between selective laser melted, milled, and hand-bent plates. Cranio-maxillofac Trauma Reconstr 2021;14:135–143
18. Ueda K, Tajima S, Oba S, et al. Mandibular contour reconstruction with three-dimensional computer-assisted models. Ann Plast Surg 2001;46:387–393
19. Derand P, Hirsch JM. Virtual bending of mandibular reconstruction plates using a computer-aided design. J Oral Maxillofac Surg 2009;67:1640–1643
20. Sharaf B, Levine JP, Hirsch DL, et al. Importance of computer-aided design and manufacturing technology in the multidisciplinary approach to head and neck reconstruction. J Craniofac Surg 2010;21:1277–1280
21. Antony AK, Chen WF, Kolokynthas A, et al. Use of virtual surgery and stereolithography-guided osteotomy for mandibular reconstruction with the free fibula. Plast Reconstr Surg 2011;128:1080–1084
22. Bell RB, Weimer KA, Dierks EJ, et al. Computer planning and intraoperative navigation for palatomaxillary and mandibular reconstruction with fibular free flaps. J Oral Maxillofac Surg 2011;69:724–732
23. Zheng GS, Su YX, Liao GQ, et al. Mandibular reconstruction assisted by preoperative virtual surgical simulation. Oral Surg Oral Med Oral Pathol Oral Radiol 2012;113:604–611
24. Shen Y, Sun J, Li J, et al. Using computer simulation and stereomodel for accurate mandibular reconstruction with vascularized iliac crest flap. Oral Surg Oral Med Oral Pathol Oral Radiol 2012;114:175–182
25. Naros A, Weise H, Tilen F, et al. Three-dimensional accuracy of mandibular reconstruction by patient-specific pre-bent reconstruction plates using an “in-house” 3D-printer. J Cranio-maxillofac Surg 2018;46:1645–1651
26. Goormans F, Sun Y, Bila M, et al. Accuracy of computer-assisted mandibular reconstructions with free fibula flap: Results of a single-center series. Oral Oncol 2019;97:69–75
27. Steffen C, Sellenschloh K, Polster V, et al. Biomechanical comparison of polylactide-based versus titanium miniplates in mandible reconstruction in vitro. *J Stomatol Oral Maxillofac Surg* 2020;121:377–382
28. Steffen C, Sellenschloh K, Vollmer M, et al. Biomechanical comparison of titanium miniplates versus a variety of CAD/CAM plates in mandibular reconstruction. *J Mech Behav Biomed Mater* 2020;111:104007
29. Al-Bustani S, Austin GK, Ambrose EC, et al. Miniplates versus reconstruction bars for oncologic free fibula flap mandible reconstruction. *Ann Plast Surg* 2016;77:314–317
30. Robey AB, Spann ML, McAuliff TM, et al. Comparison of miniplates and reconstruction plates in fibular flap reconstruction of the mandible. *Plast Reconstr Surg* 2008;122:1733–1738

31. Zhang ZL, Wang S, Sun CF, et al. Miniplates versus reconstruction plates in vascularized osteocutaneous flap reconstruction of the mandible. *J Craniofac Surg* 2019;30:e119–e125
32. Park SM, Lee JW, Noh G. Which plate results in better stability after segmental mandibular resection and fibula free flap reconstruction? Biomechanical analysis. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2018;126:380–389
33. Lim SH, Kim MK, Kang SH. Precision of fibula positioning guide in mandibular reconstruction with a fibula graft. *Head Face Med* 2016;12:7
34. Gravvanis A, Anterriotis D, Kakagia D. Mandibular condyle reconstruction with fibula free-tissue transfer: the role of the masseter muscle. *J Craniofac Surg* 2017;28:1955–1959