OPEN

Accurate Mandible Reconstruction by Mixed Reality, 3D Printing, and Robotic-Assisted Navigation Integration

Quan-quan Lin, MD,[*†] *Feng Wang, MD, PhD,*[†] *Jin-long Sun, MD, PhD,*[†] *Hai-zhong Zhang, MD, PhD,*[*] *and Qing Xi, MD, PhD*[*]

Abstract: Mandibular reconstruction is one of the most complex procedures concerning the patient's postoperative facial shape and occlusion condition. In this study, the authors integrated mixed reality, three-dimensional (3D) printing, and robotic-assisted navigation technology to complete the mandibular reconstruction in a novel and more accurate way. Mixed reality can visualize the significant anatomical structures of the operative area, but only be used in simulated operation by now. Three-dimensional printing surgical guide plate makes it easy to separate tissue, while imprecision often occurs due to the potential of displacement and deformation. In recent years, most robotic-assisted navigation surgery technology can only achieve precise position by 2D view on the screen but not realistic 3D navigation. in this study, the integrated 3 technologies were used in mandibular reconstruction. Preoperative imaging examination was performed, and the data were imported into the digital workstation before operation. First, the original data was edited and optimized to reconstruct the digital model and formulate the surgical plan. Then MR was used to output the visualized project and matched the 3D reconstruction model in reality. The 3D plate was printed for surgical guidance. Last, robotic-assisted navigation was used to guide and position the vascularized fibula autograft and the immediate dental implantation. In conclusion, the authors integrated the 3 technologies and constructed a new digital surgical procedure to improve surgical accuracy and simplify the procedure comparing with traditional surgery.

Key Words: 3D printing, digital surgery, mandible reconstruction, mixed reality, robotic-assisted navigation

(*J Craniofac Surg* 2022;33: 1720–1724)

Mandibular reconstruction is one of the most complicated maxillofacial surgeries. The oral cavity and facial region were involved in the surgery. In this area, the abundant blood vessels, complicated nerves, and irregularly distributed lymph and sinus tissues increase certain surgical risks. The complex structure also restricts operative field in deep anatomical structure. It has been reported that facial tissue displacement after surgery is one of the most frequent complications in complex mandibular reconstruction. And widespread edema in operative region and hematomas in respiratory tract cause asphyxia and massive exsanguination, which might result in shock.[1] For mandibular reconstruction, traditional construction operation is highly dependent on the experience of the surgeon. Considering the needs of intraoperative denture restoration, procedures are complicated and difficult. In recent decades, the development of digital-assisted technology provides a better solution for mandible reconstruction in more accurate and convenient occlusion reconstruction.

Mixed reality,[2] robot surgery,[3] and three-dimensional (3D) printing[4] are novel medical technologies that have provided numerous benefits to patients and surgeons. Mixed reality has been gradually developed for surgical use due to its ability to present virtual images. By facilitating preoperative communication and simulation plan, MR provides more realistic scenes and opportunities for junior doctors to understand the anatomy in surgery and master the surgical procedures.[5]

Three-dimensional printing is a tower-like technology, which is based on 3D digital model files, layers materials one upon the other, followed by postprocessing to create the final product. This process is widely employed in preoperative planning and for creating transplants and prostheses.[6] By significantly reducing the operation's difficulty, shorten the operative time, and ensure the operation's intended effect,[7] 3D printing helps surgeons implement surgical plans accurately.

In clinical practice, there are still many problems that limit 3D printing application, such as the fragility of 3D printed material, and emplacement problems. In the present study,

From the *Department of Stomatology, First Medical Center of PLA General Hospital; and †Department of Stomatology, Sixth Medical Center of PLA General Hospital, Beijing, China.
Received January 16, 2022.
Accepted for publication January 30, 2022.
Address correspondence and reprint requests to Qing Xi, MD, PhD, E-mail: xiqing301@163.com; Hai-zhong Zhang, MD, PhD, E-mail: zhanghaizhong301@aliyun.com.
Q-qL and FW contributed equally to this work.
The authors report no conflicts of interest.
This study was supported and funded by the National Key Research and Development Program (2017YFB1304300), Youth Incubation Program of Medical Science and Technology of PLA (21QNPY114).
ZH and XQ contributed to the conception and design of the study. LQ, XQ, and WF contributed to surgery operation and data acquisition, collection, and assembly. SJ, WF, and XQ contributed to data analysis and wrote the main manuscript. All authors contributed to the revision of the manuscript and approved the final version submitted for publication.

ISSN: 1049-2275
DOI: 10.1097/SCS.0000000000008603

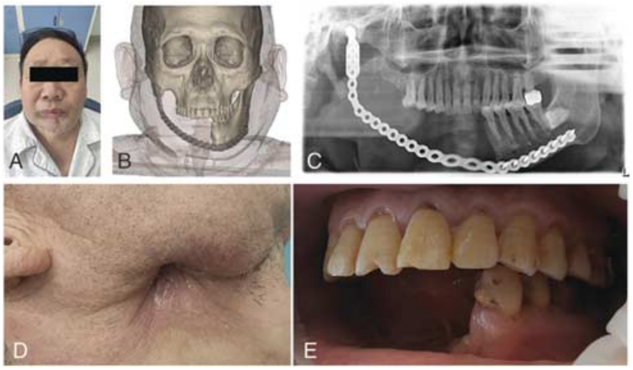

FIGURE 1. A, Preoperative frontal view. B, Preoperative computerized tomography (CT) reconstruction. C, Full-orifice curved plate. D, The lesions area. E, Occlusal condition.

we used robot navigation system (RAN) in mandibular reconstruction to avoid 3D printed material break off, and to achieve accurate emplacement. Robot navigation system surgery provides more precise positioning of the operation and smaller incisions, a reduced risk of infection, fewer postoperative symptoms, and shorter hospital stays than classical surgery[8] and is therefore widely used in departments such as general surgery,[9] hepatobiliary surgery,[10] orthopedics,[11] oph-thalmology,[12] and cardiac surgery.[13]

Nowadays, digital technology can be applied throughout the entire process of surgical planning, surgical implementation, and postoperative evaluation. With the rapid development of medical science, MR, 3D printing, and RAN have a great potential to play a key part in the future maxillofacial surgery.

METHODS

Patient's Basic Information

The present study was approved by the Ethics Committee of Chinese PLA General Hospital. The present study also followed the guidelines in the Helsinki Declaration investigation. The patient was a 67-year-old man, diagnosed with right mandibular ameloblastoma, who had undergone tumor resection, mandibular osteotomy, and mandible reconstruction by titanium plate with artificial joint head. With discomfort in the operative area and restricted mouth opening, the patient was admitted for autogenous bone reconstruction (Fig. 1). The patient has been fully informed of the advantages and disadvantages of the operation plan and the necessity of implementing this plan before the operation.

Data Collection and Reconstruction

We collected all sorts of imaging data including 3D computed tomography (CT), contrast-enhanced CT, and intraoral optical scan. The data was imported into the MIMICS system (Materialise, version 20.0) and 3-Matic system (Materialise, version 12.0) for reconstructing the mandible shape. We completed the 3D reconstruction of the skull and matched the stable occlusion within the intraoral scan in the CT reconstruction imaging. Three-dimensional printing equipment (provided by Shenzhen Putianyang Medical Instruments Co, Ltd) created the prosthesis and surgical guide plate.

After software conversions (Beijing Visual3D Medical Technology Development Co, Ltd), the surgeon can see the arteriovenous and bone tissues in reality by wearing MR glasses, which provide a more convenient and real way for preoperative discussion and simulating the surgery procedure (Fig. 2).

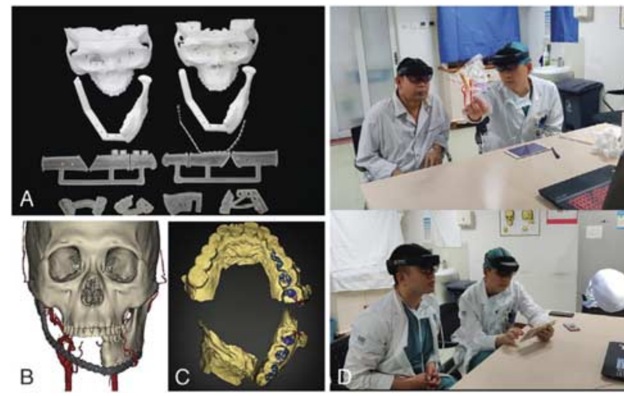

FIGURE 2. A, Three-dimensional printing of maxillofacial lesions and surgical guide plate after preoperative CT reconstruction. B, Images of preoperative enhanced CT reconstruction. C, Preoperative intraoral occlusal scanning. D, Preoperative communication and design of surgical plan by mixed reality. CT, computed tomography.

Operational Procedure

The CT data was fed into the neurosurgical robot (RM200) after scanning the patient's head attaching the stickers of the robot scanning locator (MK–06A, MK–08B, MK–06B1) on the early morning of the operation day. The navigation and position of the surgical scheme was carried out by the RAN (Beijing Baihui Weikang Technology Co, Ltd).

The titanium plate from the previous reconstruction was removed. Simultaneously, surgeons in the fibula group simulated the osteotomy range and incision of the fibular osteotomy by MR simulation.

The head and neck group dissected and shaped the fibula by 3D printing incision plate. And then, the removed fibula with the screwing hole was connected to the titanium plate which has been preadjusted on the 3D printing reconstructed mandible. Then verify the precise position of the screwing hole in the mandible and the condyle position by first RAN guidance. After that, we used the robot to verify the accurate position matched the design plan again. The implant guide plate was hired to place 4 dental implants in the horizontal segment of the fibula. Last, we verified the final location of the plate and dental implants by RAN (Fig. 3).

FIGURE 3. A, Computed tomography data was collected from locating marker and transported to the robot system. B, After the head frame was installed, the surgical robot was paired with the patient. C, Measuring the fibula area by mixed reality. D, The fibula was harvested with a guide plate during the operation. E, The operative plan was verified by mixed reality after the surgery.

FIGURE 4. A, Reexamination in early September 2020, 1 day after surgery. B, Reexamination in early October 2020,1 week after surgery. C, Reexamination in early November 2020, 1 month after surgery. D, Reexamination in early November 2020, 2 months after surgery.

RESULTS

In the design of the surgical plan, MR was employed to visualize the surgical plans preoperatively and simulate the completed operation procedure in the confirmed surgical area. To prevent complications and perform more accurate operation, we used 3D printing technology to create preoperative surgical prosthetic prefabrication, intraoperative osteotomy, and insertion guide plates. Then we shaped the fibulas and guided the autograft into the exact location. Subsequently, the RAN technology was applied determine the condyle position and the mandible screwing hole. After the autografts to be reconstructed, we screwed the 4 implants into the autogenous bone. Finally, we verified the current surgical process, and the position was the same as designed by RAN.

The operation was successfully completed by combining application of the 3 techniques. The patient was reexamined at 1 week, 1 month, and 6 months after the operation (Fig. 4). The bilateral condyles degree in the glenoid fossa is in the correct trajectory.

There was no bone exposed or skin fistula, and the range of the mouth opening degree was the same as preoperation. The mucosa of operative area in oral cavity was healthy and the patient has the centric occlusion relation. The CT results showed that the reconstructed bone connection and artificial condyles position was correct (Fig. 5). Therefore, we validated the surgical process by using digital technology in each step of the operation, to avoid various minor errors which often occurred in traditional surgery, and to ensure the outcome was the same with the preoperative design.

DISCUSSION

Compared with classical methods, the step-by-step verification integrating the 3 technologies (MR, 3D printing, and RAN) provides the advantages of a significantly shortened operative time, less intraoperative bleeding, and accurate positioning ofthe operation. There have been no reports in the literature in the past 10 years about combining the 3 technologies for mandible reconstruction. The study verified the novel digital surgical procedure by reconstructing the mandibular defect, which has provided a new strategy for reconstructing maxillofacial tissue defects.

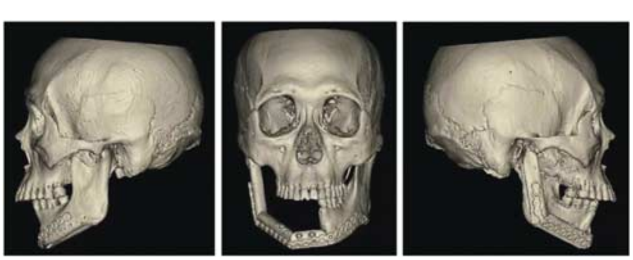

FIGURE 5. Reconstruction computer tomography images 3 months after the surgery.

Mixed Reality

Mixed reality, both preoperatively and intraoperatively, can directly display the positional relationship between important anatomical structures, neurovascular, and tumor lesions. Mixed reality helps patients understand their own conditions and assist surgeons in simulating the dissection, separation, and positioning during the surgery. While teaching young residents, using a head-mounted display to show 3D models is significantly easier and more intuitive than using 2D pictures.[14]

Given that the technology is novel, MR is still not perfect for clinical use. The equipment can be relatively heavy (approximately 3 kg), increasing the pressure on the surgeon's cervical spine. The imaging resolution of most MR machines also fails to match the retina's level, and the imaging and actual position can deviate due to changes in the position of the head-mounted display. Besides, the operation of MR can be complicated, requiring the assistance of a third party.[15]

Despite these problems, our group is still committed to actively developing a new kind of accurate AI portable surgical glasses with real-time navigation function, to reducing the difficulty of preoperative communication, shortening the operation time, reducing intraoperative bleeding, enhancing the operational accuracy, and lowering the risk of surgery in the future development.

Three-Dimensional Printing

Accomplishing the data collection, we employed 3D printing to create a preoperative skull defect model, visualized and analyzed the bone defect lesion, and formulated the surgical plan. The personalized surgical guide plate was used to facilitate the fibular osteotomy, shaping, and the final fixation.

In addition, the patient's occlusion might switch from a central position to mandibular retrusion due to changes in body position during CT imaging, which would increase the difficulty of the postoperative repair and lead to malocclusion. Based on above, the intraoral scan data were reconstructed and matched with the 3D CT data to ensure the accuracy and stability of the patient's occlusion position.

Dr Chuck Hull invented 3D printing technology in 1986,[16] which was first used in head and neck surgery in 1987 by Dr Brix and Dr Lambrecht.[17] Three-dimensional printing is widely served in orthopedics, general surgery, and personalized rehabilitation. There have been numerous reports in the literature on the clinical applications of 3D printing in the field of stomatology, including head and neck surgery, orthognathic surgery, prosthetics, endodontics, and periodontology.[18] We found that 3D printing facilitates preoperative visualization, surgery planning, accurate positioning, and better fitting of reconstruction titanium plates during operations compared with classical surgical methods. Three-dimensional printing significantly shortens the operative time, improves the accuracy of the operative area, and reduces intraoperative trauma. Three-dimensional printing is therefore suitable for maxillary/mandibular reconstruction and orthognathic surgery. Foley retrospectively studied 8 cases in which 3D printing was applied to create surgical guide plates and prebent reconstruction titanium plates in the presence of free bone flaps to repair massive mandibular defects.[19]

Although 3D printing has certain indisputable advantages, it does have some problems. In most cases, the final product of 3D printing is brittle and fragile, and the surface accuracy is relatively low. With the new technology, Foley confirmed that the error in the front and back direction was 0 to 0.7 mm, the error in the distance between bilateral condyles was 0.7 to 4.5 mm, and the distance between the bilateral mandibular angles was 0.7 to 4.8 mm. Roser et al[14] selected 19 patients for whom computer-assisted design, osteotomy and shaping guide plates, and prebent reconstruction titanium plates were employed to complete the repair of mandibular defects with fibular flaps. The patients' actual postoperative mandibular and fibular osteotomy line and the fitness of the reconstruction titanium plates were compared with that of the preoperative design. The authors found that the mean error of the mandibular and fibular osteotomy line was 2.00 ± 1.12 and 1.30 ± 0.23 mm respectively. The fitness of the prebent reconstruction titanium plates with that of the preoperative design was 58.73% ± 8.96%. The study indicated that the largest error occurred in the manual reconstruction titanium plate and showed the reliability of the digital surgical technology in the reconstruction of mandibular defects.

From what has been discussed above, we need a way to correct the inaccuracies caused by the deformation and dislocation of 3D printing materials, so we attend to the RAN system.

Robotic-Assisted Navigation

Combined application of MR and 3D printing in orthopedics and general surgery provides surgeons with high work efficiency and reduces the risk of intraoperative traumatic bleeding and postoperative complications. But the position of the connected screwing hole on the residue mandible was hard to achieve by subjectively predicting the position through experience or guide plate in the traditional surgery.

Therefore, for the first time, our group employed a neurosurgical robot (RM200) to conduct the navigation and positioning during the surgery. The robot has been served in surgical approaches for skull base surgery and endoscopic neurosurgery due to its accurate navigation and positioning ability.[20] In oral and maxillofacial surgery, robot navigation and positioning can be applied to the following operations[21]: maxillofacial salivary gland tumor ectomy, cervical lymphadenectomy, zygomatic-orbital-maxillary fracture repair, digital implant surgery, etc. Especially for repairing severe periorbital fractures,[22] surgical navigation is of great utility for effectively correcting the eyeball's position and symmetry,[23] restoring the orbit volume, and correcting endophthalmitis and diplopia.[24]

If robots can be employed to perform 3D visualization of intraoperative positioning, we will achieve desirable results in maxillofacial surgery compared with classical surgery, which will effectively reduce surgical trauma and maximize the retention and recovery of the patient's function and appearance.[25] However, navigation and positioning robots are large, difficult to move, incompatible with conventional operating tables and anesthesia machines, complicated to position before surgery, and expensive, which restrict their rapid development. Nevertheless, their main drawback is their lack of tactile feedback during the operation. Maxillofacial anatomy is complex, composed mainly of soft tissues, and there is no special device at this moment for such surgery. Reaching the maxillofacial operative area directly is also difficult due to its unique anatomy.[26] In plastic and reconstructive surgery, robotic surgery is often associated with an increased risk of tissue injury due to the aforementioned reasons, especially in the absence of relevant experience.[27] The clinical application of robotic surgery is still in its infancy, but with the development of this technology, the focus of future research will lie in specialized robots and relevant devices for cranial-maxillofacial surgery, simulation based on tactile feedback,[28] and remote surgery.[29] In this study, 3D printing guide plates can assist RAN to be more accurate in the manipulation.

Therefore, MR, 3D, and RAN technologies assist each other to make the surgery more accurate and minimally invasive. Digital surgery technology has made significant progress by now. A number of teams have conducted a series of studies on robots designed for mandible reconstruction and paracentesis at the base of the skull which provide new strategies for head and neck tumors and for reconstruction operations. However, the studies are still in the modeling and animal experiment stage. Through our efforts, we have established a future digital surgery platform based on the mutual authentication of MR, 3D printing, and RAN which focused on accuracy, making it a development trend for oral and maxillofacial surgery.

REFERENCES

1. Louis PJ, Morlandt AB. Advancements in maxillofacial trauma:a historical perspective. *J Oral Maxillofac Surg* 2018;76:2256–2270
2. Verhey JT, Haglin JM, Verhey EM, et al. Virtual, augmented, and mixed reality applications in orthopedic surgery. *Int J Med Robot* 2020;16:e2067
3. Louvrier A, Marty P, Barrabe A, et al. How useful is 3D printing in maxillofacial surgery? *J Stomatol Oral Maxillofac Surg* 2017;118:206–
4. D'Souza M, Gendreau J, Feng A, et al. Robotic-assisted spine surgery:history, efficacy, cost, and future trends [published correction appears in Robot Surg. 20*19 Dec 23;6:25]. *Robot Surg* 2019;6:9–23
5. Bernardo A. Virtual reality and simulation in neurosurgical training. *World Neurosurg* 2017;106:1015–1029
6. Zhong N, Zhao X. 3D printing for clinical application in otorhinolaryngology. *Eur Arch Otorhinolaryngol* 2017;274:4079–4089
7. Martelli N, Serrano C, van den Brink H, et al. Advantages and disadvantages of 3-dimensional printing in surgery:a systematic review. *Surgery* 2016;159:1485–1500
8. McDermott H, Choudhury N, Lewin-Runacres M, et al. Gender differences in understanding and acceptance of robot-assisted surgery. *J Robot Surg* 2020;14:227–232
9. Park SH, Hyung WJ. Current perspectives on the safety and efficacy of robot-assisted surgery for gastric cancer. *Expert Rev Gastroenterol Hepatol* 2020;14:1181–1186
10. Roh HF, Nam SH, Kim JM. Robot-assisted laparoscopic surgery versus conventional laparoscopic surgery in randomized controlled trials:a systematic review and meta-analysis. *PLoS One* 2018;13: e0191628
11. Chen X, Feng F, Yu X, et al. Robot-assisted orthopedic surgery in the treatment of adult degenerative scoliosis:a preliminary clinical report. *J Orthop Surg Res* 2020;15:282
12. Urias MG, Patel N, He C, et al. Artificial intelligence, robotics and eye surgery:are we overfitted? *Int J Retina Vitreous* 2019;5:52
13. Balkhy HH, Amabile A, Torregrossa G. A shifting paradigm in robotic heart surgery:from single-procedure approach to establishing a robotic heart center of excellence. *Innovations (Phila)* 2020;15:187–194
14. Foley BD, Thayer WP, Honeybrook A, et al. Mandibular reconstruction using computer-aided design and computer-aided manufacturing:an analysis of surgical results. *J Oral Maxillofac Surg* 2013;71:e111–e119
15. Huang TK, Yang CH, Hsieh YH, et al. Augmented reality (AR) and virtual reality (VR) applied in dentistry. *Kaohsiung J Med Sci* 2018;34:243–248
16. Mehra P, Miner J, D'Innocenzo R, et al. Use of 3-d stereolithographic models in oral and maxillofacial surgery. *J Maxillofac Oral Surg* 2011;10:6–13

17. Morris CL, Barber RF, Day R. Orofacial prosthesis design and fabrication using stereolithography. *Aust Dent J* 2000;45:250–253
18. Oberoi G, Nitsch S, Edelmayer M, et al. 3D printing-encompassing the facets of dentistry. *Front Bioeng Biotechnol* 2018;6:172
19. Bolzoni AR, Segna E, Beltramini GA, et al. Computer-aided design and computer-aided manufacturing versus conventional free fibula flap reconstruction in benign mandibular lesions: an Italian cost analysis. *J Oral Maxillofac Surg* 2020;78:, 1035.e1–L 1035.e6
20. Austin GK, McKinney KA, Ebert CS Jr, et al. Image-guided robotic skull base surgery. *J Neurol Surg B Skull Base* 2014;75:231–235
21. Paleri V, Fox H, Winter S. Transoral robotic surgery for oropharyngeal cancer. *ORL J Otorhinolaryngol Relat Spec* 2018;80:156–170
22. Chen X, Lin Y, Wang C, et al. A surgical navigation system for oral and maxillofacial surgery and its application in the treatment of old zygomatic fractures. *Int J Med Robot* 2011;7:42–50
23. Schramm A, Suarez-Cunqueiro MM, Rücker M, et al. Computerassisted therapy in orbital and mid-facial reconstructions. *Int J Med Robot* 2009;5:111–124
24. Yu H, Shen G, Wang X, et al. Navigation-guided reduction and orbital floor reconstruction in the treatment of zygomatic-orbital-maxillary complex fractures. *J Oral Maxillofac Surg* 2010;68:28–34
25. Zanagnolo V, Garbi A, Achilarre MT, et al. Robot-assisted surgery in gynecologic cancers. *J Minim Invasive Gynecol* 2017;24:379–396
26. Lee HS, Kim WS, Hong HJ, et al. Robot-assisted Supraomohyoid neck dissection via a modified face-lift or retroauricular approach in early-stage cN0 squamous cell carcinoma of the oral cavity: a comparative study with conventional technique. *Ann Surg Oncol* 2012;19:3871–3878
27. O'Malley BW Jr, Weinstein GS. Robotic skull base surgery: preclinical investigations to human clinical application. *Arch Otolaryngol Head Neck Surg* 2007;133:1215–1219
28. Binet A, Ballouhey Q, Chaussy Y, et al. Current perspectives in robotassisted surgery. *Minerva Pediatr* 2018;70:308–314
29. Leal Ghezzi T, Campos Corleta O. 30 years of robotic surgery. *World J Surg* 2016;40:2550–2557

