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Patient-Specific 3D-Printed Cutting and Repositioning Guide for Mandibular Tumor Resection: Surgical Design and Validation

Khawla H. Rasheed
Ibn Sina University of Medical and Pharmaceutical Sciences

Auns Qusai Al-Neami
Al-Nahrain University

Haider Al-Alawi
Ghazi Al Hariri Hospital

Abstract: Mandibular tumor resection poses significant surgical challenges in terms of achieving precision and restoring anatomical symmetry. Virtual surgical planning (VSP) combined with 3D printing offers a promising solution through the use of patient-specific guides. A workflow integrating CBCT imaging, segmentation using Mimics and 3-Matic, and design of patient-specific cutting and repositioning guides was developed. A 52 years old patient with squamous cell carcinoma was treated using this approach, and the guides were fabricated from PLA with dimensions tailored to the patient and case specific dimentions. The cutting guide ensured tumor-free margins while conserving as much as possible of healthy bone. The repositioning guide restored anatomical alignment with high accuracy. Guides were lightweight, very precisely adapted, and demonstrated surgical feasibility and reproducibility. This study presents a streamlined, low-cost approach to mandibular tumor resection using 3D-printed guides. The workflow allows for reproducible surgical outcomes without the need for intraoperative navigation.

Keywords: 3D-printing, Mandibular tumor, Surgical guides, Virtual surgical planning

Introduction

Virtual surgical planning (VSP) integrates imaging, Computer Aided Design (CAD), and 3D printing to create patient-specific guides that translate virtual osteotomies into the operating room (Gazo Hanna et al., 2024). High-resolution computed tomography (CT) is first used to capture the tumor and bony anatomy (Thayaparan et al., 2021). The DICOM (Digital Imaging and Communication in Medicine) data are segmented into 3D models of the skull and tumor using software (e.g., Materialise ProPlan, 3D- slicer) (Evans et al., 2023). Surgeons then define resection planes and safety margins on the 3D model. Custom cutting guides (shells that fit the bone and include screw openings) and, if needed, repositioning templates for free flaps are designed in CAD (e.g., SolidWorks or Materialise 3Matic) (Park et al., 2025). These guides are 3D-printed in biocompatible materials typically biocompatible resins (via stereolithography/ Digital Light Processing printers (DLP) printers) or metals (via powder-bed fusion) (Iocca et al., 2024). Intraoperatively, the guide uniquely fits the bone and constrains the saw to the planned cuts, so that the virtual osteotomy is executed precisely (Bleys et al., 2023). A typical workflow of this procedure is: (1) CT or and sometimes Magnetic resonance images (MRI) imaging; (2) segmentation to STL models; (3) virtual osteotomy planning; (4) design of cutting/repositioning guides; (5) 3D printing of guides; (6) surgical use of guides to execute resections. Advances such as virtual/augmented reality are also being integrated to improve planning and post-op analysis (Wilkat et al., 2021).

In other hand workflow steps include Imaging: Acquire high-resolution CT and sometimes MRI of the tumor and facial skeleton. Segmentation: Convert DICOM images to 3D digital models (STL) of the mandible, maxilla, tumor, etc., using medical imaging software. Planning: Define osteotomy planes and 3D resection margins on the model (often adding ~10 mm safety margins). Guide Design: Create patient-specific cutting guides, typically a fit-to-bone "shell" plus a saw guide, 3D Printing: Fabricate the guides using 3D printers (SLA/DLP for resins or PBF for metals) with biocompatible, sterilizable materials. Surgery: Intraoperatively, the surgeon applies each guide to the bone (e.g., mandible or midface) so that saw cuts follow the preplanned orientation (Weijs et al., 2025). Often a second guide then positions the remaining free segments onto normal anatomical position, locking in the planned alignment (Bleys et al., 2023).

There are many methods of segmentation that are often used in this field. Manual segmentation, which considered a gold standard for detail, but is extremely labor-intensive and operator-dependent. Studies report very high intra-operator variability (manual segmentations can err by tens of percent, making it slow and less practical for routine use (de Boer et al., 2023). Semi-automatic segmentation uses tools like thresholding or region-growing to accelerate labeling. In head/neck tumor studies it yields nearly identical volumes to manual (Dice ≈0.87–0.97, ICC ≈0.99) (Lo Giudice et al., 2020). However, accuracy is comparable to manual and total segmentation, time is often similar ease of use is moderate (it still requires user oversight and some editing) (Xie et al., 2025).

AI-based segmentation deep-learning models now achieve expert-level accuracy on CMF data (often Dice >0.9) (Jiang et al., 2025) and drastically reduce user effort. For example, a validated AI method erred by <2% in volume vs ground truth, while manual labels showed ~50–70% error (Matias et al., 2017). This means AI can vastly speed up planning, but real-world reliability depends on large training sets and thorough validation in varied tumor cases.

In mandibular tumor surgery, superimposed planned (color) versus actual (gray) 3D models show guide accuracy (Iocca et al., 2023). Mandibular protocols usually involve a few weeks' lead time where patients undergo CT imaging 2- 4 weeks before surgery, allowing engineers to segment the bone and tumor, plan cuts in software, and design guides (You et al., 2021). Intraoperatively, applying the mandible guide yields the planned resection plane exactly (as long as the tumor has not grown beyond the planned margins). Importantly, one reported series used a 10 mm planning margin in 16 mandibular cancer cases and achieved 100% (tumorfree) bone margins. This suggests that when carefully planned, VSP-guided mandibular resections can reliably achieve safe oncologic outcomes (Weissheimer et al., 2012). In other words, virtually planned cuts are replicated extremely closely in surgery. The clinical payoffs include more predictable reconstructions and in many cases shorter operative time and less guesswork. Importantly, studies report extremely low recurrence/margin failure (Lo Giudice et al., 2022). Despite these successes, practical challenges are still. Planning and guide fabrication incur extra cost and preoperative time. A considerable time gap (often 3-6 weeks) can elapse between imaging and surgery, raising concern for tumor progression. Some studies showed that delayed cutting guides sometimes did not match the enlarged tumor, and 3D-printing companies may not rapidly deliver (Knoops et al., 2019). To mitigate this, some centers print in-house to shorten turnaround. Other potential issues are guiding misfit (if anatomy changes), learning curves for the software workflow, and the need for regulatory approval of custom devices. Notably, no research reported guide-related complications, in fact, guided cases generally had similar or lower complication rates (e.g., flap failures) compared to controls, although few studies reported this data explicitly. Looking forward, innovations continue to appear. Some teams now integrate virtual/augmented reality to plan and even to guide surgery intraoperatively (Yu et al., 2020; Argüello et al., 2019). As 3D printers and VSP software become faster and cheaper, the workflow is likely to become more streamlined. In summary, recent literature (2019–2024) shows that VSP with patient-specific cutting guides is a validated, practical advance for CMF tumor resections. These tools improve surgical accuracy and predictability in both mandibular and midfacial oncologic surgery, at the cost of additional planning time and expense (Matsiushevich et al., 2019).

Although virtual surgical planning (VSP) and additive manufacturing are increasingly used in craniomaxillofacial (CMF) surgery, a clear and standardized workflow that connects digital planning with real-world surgical applications, especially in complex mandibular reconstructions is still lacking. This study introduces and clinically validates a practical, patient-specific workflow that integrates cutting and repositioning guides for cases involving significant anatomical condition, such as tumors. By combining high-resolution imaging, precise segmentation, and virtual surgical simulation with careful intraoperative application, this approach enhances surgical accuracy and improves both functional and aesthetic results. Beyond demonstrating technical feasibility, the workflow aims to improve surgical efficiency, support safer patient outcomes, and simplify complex procedures. The insights shared in this study may be particularly valuable for surgeons, engineers, and researchers who are advancing digital technologies in everyday clinical practice.

Method

A preoperative CBCT scan of 52 years old patient with squamous cell carcinoma with 0.5 slice thickness were obtained and stored in DICOM file format to obtain detailed 3D representation of tumour margins, as shown in Figure 1. DICOM file imported to Mimics 21 software for segmentation and calculation of 3D part of mandible, as shown in Figure 2. 3-Matic 13 and Proplan CMF 3 where used for surgical planning and design. Prior to this study, we conducted an internal comparison of leading segmentation platforms (Materialise Mimics, ProPlan CMF, 3D Slicer, etc.) and found small differences in volumetric accuracy, although Mimics yielded the highest voxel counts. Based on these results, all cases were segmented in Mimics 21.0 (Materialise, Leuven, Belgium) (Rasheed et al., 2023). In Mimics we applied standard bone-thresholding and region-growing to isolate the mandible (and any graft segments) from surrounding tissues. Segmented masks were converted to 3D surface models for planning. This step ensured highly precise anatomical reconstructions of 3-D patıent mandible model model (Huang et al., 2025).

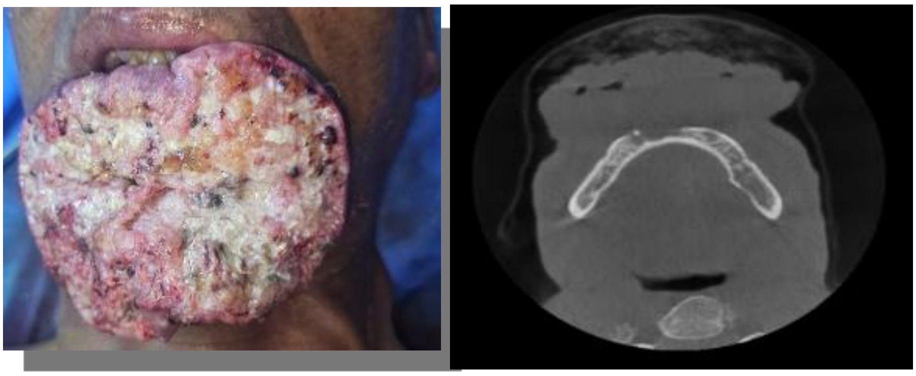


Figure 1. 52 years old patient with squamous cell carcinoma (left: patient image, right: CBCT).

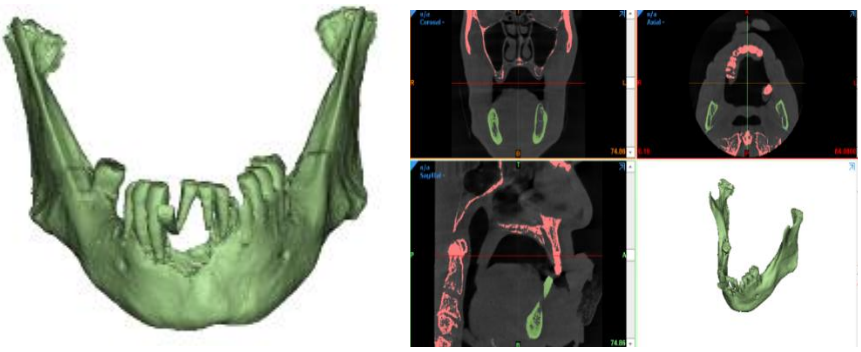


Figure 2. 3D part of mandible for patients with lower lip squamous cell carcinoma. Segmentation of mandible LT, 3D objects RT.

Osteotomy lines were determined to achieve a balance between complete tumor resection and preservation of healthy bone. The referencing used for this case is the RT and LT mental foramens, where the cutting plane of left side was at the anterior border of mental foramens and for the right side was 5 mm posterior to the posterior border of mental foramens, as shown in Figure 3. The osteotomy planes that needed for the mandibulectomy were defined. Each cutting plane was oriented with respect to stable anatomical landmarks (for example, the mental foramina, mandibular condyles, and gonial angles) to standardize positioning. The 3D osteotomy lines were drawn on the model at the planned locations and angles. Then the plan transferred to Materialise 3-matic 13.0 for guide design. In 3-matic, Patient-specific cutting guides were generated by first creating a 2 mm thick capsule structure. The cutting edges were designed with a thickness of 4 mm to ensure stability during osteotomy. This capsule was then sectioned and reshaped to match the desired guide design, conforming closely to the patient's anatomical features. Likewise, repositioning guide was 3 mm thick. It shaped to mate with the remaining mandibular stumps and to align with the fixation strategy. All guide geometries were fitted tightly to the bony surfaces around the osteotomy regions, ensuring stable engagement.

A cutting guide was designed for each side (LT and RT), angle of the mandible was used as posterior reference while the same planes used to cut the mandible virtually were used as an interior reference (Figure 4). A virtual resection of the affected mandibular segment was performed to visualize postoperative anatomy and facilitate planning.

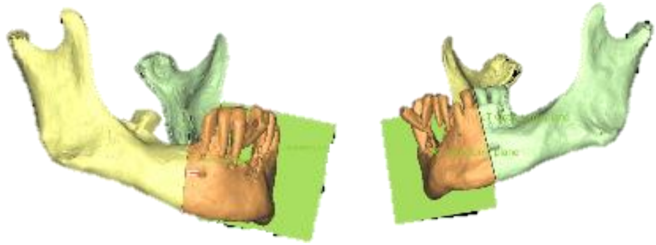


Figure 3. Mental foramens used as references for cutting planes, of left side at the anterior border of mental foramen (LT), cutting plane of right side 5 mm posterior to the posterior border of mental foramen (RT).

Figure 4. Left and right cutting guides (in pink), affected part of mandible (in purple).

After cutting the middle portion of the mandible the left and right pieces mostly would lose their normal anatomical position. Reconstructive planning included determining bone alignment and adaptation for stabilization. So, the repositioning guide is designed to keep them in normal position as shown in Figure 5. The cutting and repositioning guides were designed in away keeping them as small as achievable.

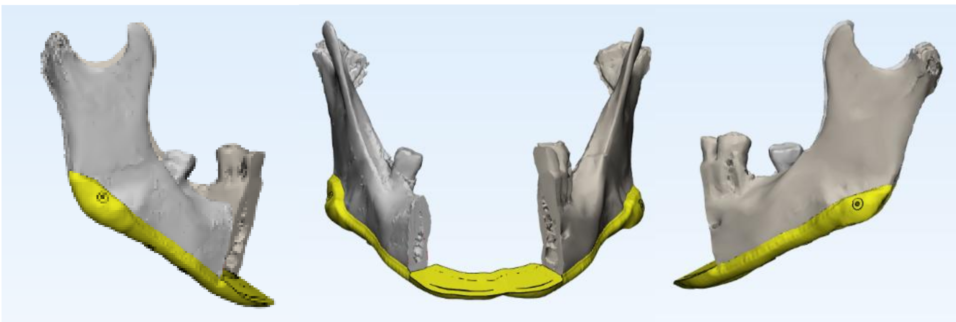


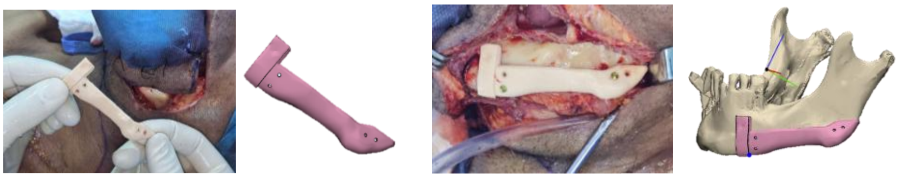
Figure 5. Repositioning guide designed to keep RT and LT mandibular segments in their normal anatomical position.

The designed patient specific cutting guides and repositioning guide with bone parts are exported in STL file format and 3D printed. This step is important to show final results, physical visualization and sometimes to conduct simulated operations. These printed objects help in accurately transferring the surgical plan to the actual surgery, ensuring precision and reducing operative time. Material used PLA (Poly Lactic Acid polymer) which could be assumed as biologically friendly material. The printer used is Creality K1C printer.

These printed models serve as valuable tools for pre-surgical assessment, allowing the surgical team to visualize anatomical details, validate the virtual plan, and confirm the fit of the occlusal splint. The models also facilitate communication between the surgical and technical teams, ensuring precise transfer of the virtual plan to the operating room. The small guides can be placed and secured intraoperatively with minimal soft-tissue retraction. İts found that, this technique to be highly straightforward (Rodríguez-Arias et al., 2024). In practice, the cutting guide seats onto the mandible using its custom-molded fit, and the surgeon slides the osteotome through the thickend edge suuport. A corresponding repositioning guide then aligns the residual segments for fixation.

Results and Discussion

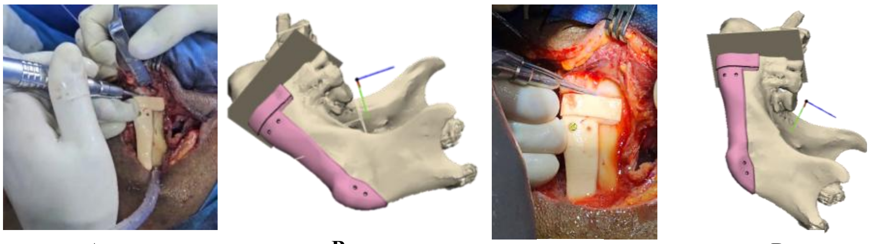
The surgery was conducted at Operation Theatre, Gazi Alhariri hospital medical city. The first step involved the removal of the affected part of the mandible using 3D-printed, patient-specific cutting guides. These guides are designed carefully with high attention to ensure that osteotomy includes all the tumor margins while preserving as much healthy tissue as possible. Figure 6 shows a comparison between the virtual surgical plan and its translation to the real world. Where Figure 6 (A) shows the designed cutting guide (right), and the 3D printed cutting guide (before fixing it to the patient mandible. (Figures 6B and C) demonstrate the cutting guide fitted to the 3D mandible model (right) and the 3D-printed cutting guide fixed to the patient's mandible (left), respectively.



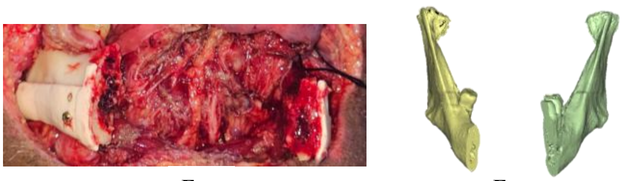
(A) **(B)**

(C)

Figure 6. A comparison between the virtual surgical plan and its translation to the real world. Figure 6 A shows the designed cutting guide (right), and the 3D printed cutting guide (before fixing it to the patient mandible. (Figures 6B and C) the cutting guide fitted to the 3D mandible model (right) and the 3D-printed cutting guide fixed to the patient's mandible (left), respectively.



A **B** **C** **D**



E **F**

Figure 7. The process of bone osteotomy in the real world (Figures 7A and 7C) and in the virtual environment (Figures 7B and 7D), alongside the resulting osteotomy (Figures 7E and 7F).

Cutting guides are designed to conform precisely to the patient's unique anatomy, ensuring that osteotomies are performed with high precision. This minimizes the risk of incomplete tumor resection or excessive removal of healthy bone (Jiang et al., 2025). providing a simple and accurate template for bone cutting, these guides simplify the surgical process, reducing operative time (Wallner et al., 2019). In other hand if the tumor is invaded complex or critical structures these guides will gives surgeons more confidence during operation (Mandolini et al., 2022). Figure 7 illustrates the process of bone osteotomy in the real world (Figures 7A and 7C) and in the virtual environment (Figures 7B and 7D), alongside the resulting osteotomy (Figures 7E and 7F).

Following the resection of the affected mandibular bone segment, a patient-specific repositioning guide was used to ensure precise alignment of the remaining bone segments to its normal anatomical position and to achieve proper occlusion, to restore anatomical continuity and functionality. The repositioning guide fitted easily and precisely to patient anatomy. Two repositioning guides were designed during the design procedure. However, upon 3D printing the mandible and guide, it was discovered that placing the guide on the mandible was not easy. As a solution, another guide was designed with a surface offset of 0.3 mm. This modification made fitting the guide onto the mandible much easier. Figure 8 shows a comparison between the repositioning guide in virtual environment and its precise fitting to patient mandible segments. The repositioning guide was fabricated from sterilizable medical-grade resin, using a high-resolution 3D printing process.

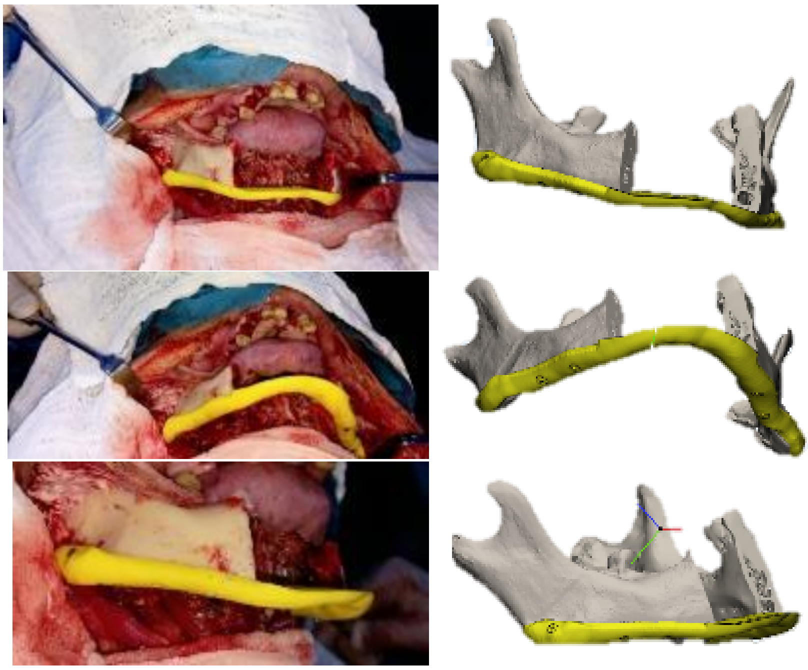


Figure 8. A comparison between the repositioning guide in virtual environment and its precise fitting to patient mandible segments.

The last step was mandible reconstruction using titanium reconstruction plate of 11 Hole, straight, 2.7 mm system. One day before surgery, the plate adapted to the 3D printed patient mandible model (Figure 9A). This plate was 2.5 mm thick, so the mandible was intruded 2.5 mm to ensure that it would take normal shape and curvature of the mandible (Figure 9B).

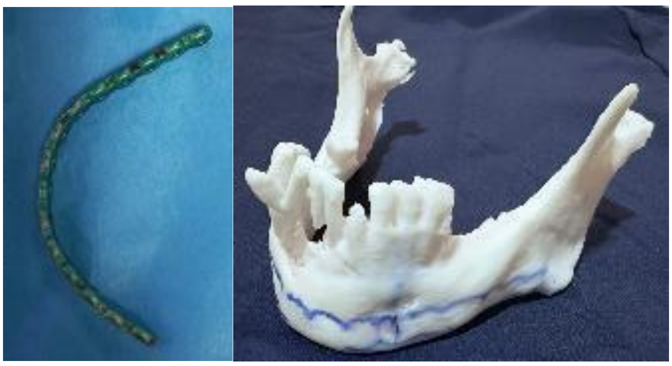


Figure 9. Adaptation of the 3D printed patient mandible model (Figure 9A). intruded mandible (Figure 9B).

The plate is fixed to mandible segments using titanium screws 2.7mm in diameter and 11mm length. The fixation of reconstruction plate was too easy due to presence of repositioning guide which held the mandible segments in their normal positions, as shown in Figure 10 (A and B). Peer-reviewed series uniformly demonstrate that VSP plus patient-specific guides yield high accuracy and favorable outcomes. Accuracy metrics from multiple studies clusters around 1-3 mm and a few degrees. reported mean osteotomy errors ≈1.5 mm (de Boer et al., 2023), Iocca et al. found angular deviations ~5–6° and submillimeter alignment errors (Iocca et al., 2024), and Park et al. saw higher negative margin rates in the guided group (Park et al., 2025).

Unlike previous reports that relied on intraoperative navigation, our workflow used only the 3D-printed guides and anatomical landmarks. For example, Yao et al. combined multiple patient-specific plate guides with an optical navigation system (Yu et al., 2020). They imported the guiding plate into the navigation console and used landmark points on the plate to register the mandible in real time. In that series, different custom plates were used for each defect and final alignment was guided by intraoperative navigation, yielding an average osteotomy error (shift) under 5 mm (Ter Braak et al., 2020; Dahake et al., 2017).

Figure 10. Fixation of reconstruction plate (A) mandible segments in their normal positions (B).

In contrast, our method achieves comparable precision without any navigation hardware. All registration is achieved purely by the precise fit of the guide to the bone. Intraoperatively we simply place the cutting guide against the mandible at the marked landmarks and perform the osteotomy, the plan transfers directly via the guide geometry. Despite this simpler and lower-cost approach, the resulting accuracy is on par with that reported in navigation-assisted series (Willinger et al., 2021). Many studies report very high precision using VSP-guided cutting guides. For example, Suhaym et al. (Saudi Dent J 2024) measured the discrepancy between planned and actual mandibular osteotomies in 14 cancer patients and found a mean error of only 1.52 ± 1.02 mm. They concluded that "3D-printed cutting guides are a very accurate and reliable tool" for translating the plan to surgery (Iocca et al., 2024). Likewise, Iocca et al. (Frontiers 2025) evaluated 17 fibula-free-flap mandible reconstructions with in-house VSP and custom cutting/repositioning guides. They reported mean angular deviations of ~5-6° and translation errors of ~1-2 mm in both mandibular body and ramus osteotomies (de Boer et al., 2023). All these findings indicate that the guides allow surgeons to achieve the intended osteotomies with millimetric accuracy.

Conclusion

The use of 3D-printed, patient-specific cutting guides greatly enhanced the accuracy of mandibular resection. These guides ensured complete tumor removal while preserving as much healthy tissue as possible, translating the virtual surgical plan seamlessly into the operative setting. The repositioning guides proved to be highly effective in restoring the normal anatomical alignment of mandibular segments, ensuring functional occlusion and contributing to both functional and aesthetic outcomes. Adjustments to the design (e.g., surface offset) improved usability, highlighting the importance of iterative design in surgical tools. The presence of the repositioning guide during the final reconstruction step simplified the fixation of the titanium reconstruction plate, improving intraoperative workflow and ensuring accurate mandibular curvature and stability. The innovation in this work is a reduction of complexity using compact, patient-specific PLA guides to reliably reproduce the virtual osteotomy without additional tracking equipment. This streamlines the surgical workflow and greatly reduces expense, while still maintaining the high accuracy reported by more elaborate systems. Where This study contributes to the field by validating a simplified yet accurate workflow for designing and applying patient-specific cutting and repositioning guides, which can be reproduced without surgical navigation systems. Future studies could focus on desighning adaptable cutting guides that could be used for more than one patient.

Recommendations

As mandibular tumors has progression and anatomical changes, it is strongly recommended that the workflow be tightly integrated between surgeons, biomedical engineers, and 3D printing specialists. Such coordination minimizes delay that may lead to misfitting of the designed surgical guides, ensuring timely and accurate application during surgery.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that there are no conflicts of interest regarding this work.

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Author(s) Information

Khawla H. Rasheed
Ibn Sina University of Medical and Pharmaceutical Sciences, College of dentistry, Baghdad, Iraq
Contact e-mail: *eng.khawlarasheed@gmail.com*

Auns Qusai Al-Neami
Al-Nahrain University, College of Engineering, Biomedical Engineering Department, Baghdad, Iraq

Haider Al-Alawi
Ghazi Al Hariri Hospital, Department of Oral and Maxillofacial Surgery, Medical City, Baghdad, Iraq

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