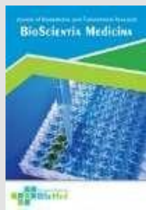

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In-House Virtual Surgical Planning Using 3D Slicer: Outcomes of Free Fibular Flap Mandibular Reconstruction

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A B S T R A C T

Background: Mandibular reconstruction following tumor resection remains a significant surgical challenge requiring precise restoration of facial symmetry and function. Virtual surgical planning has emerged as a transformative approach, yet its adoption remains limited by the high costs of commercial platforms and proprietary cutting guides. **Methods:** This proof-of-concept case series evaluated the operative outcomes and cost-effectiveness of an in-house virtual surgical planning workflow using 3D Slicer, a free open-source software platform, for mandibular reconstruction with free fibular flap without fibular cutting guides. **Results:** Four consecutive patients (three males, one female; mean age 39.0 years; standard deviation 13.1; range 28-58) who underwent mandibular reconstruction between July and December 2024 were included. Three patients presented with ameloblastoma and one with squamous cell carcinoma. Preoperative computed tomography data were processed using 3D Slicer version 5.6.2 to generate three-dimensional mandibular models through thresholding segmentation, followed by mirroring technique reconstruction and polylactic acid three-dimensional printing. The mean ischemic time was 51.0 minutes (standard deviation 10.7; 95% confidence interval 34.0-68.0), representing a 70.4% reduction compared with conventional approaches in published literature. The mean total operative time was 455.0 minutes (standard deviation 136.5; 95% confidence interval 237.8-672.2). Model printing costs of IDR 50,000-100,000 (approximately USD 3-7) represented a 99% reduction compared with commercial cutting guides. **Conclusion:** All flaps survived without complications. These preliminary findings suggest that simplified in-house virtual surgical planning using free open-source software provides a potentially cost-effective and efficient alternative for mandibular reconstruction, warranting validation in larger prospective studies.

1. Introduction

Mandibular tumors represent a significant proportion of oral and maxillofacial pathology worldwide. Ameloblastoma, the most common odontogenic tumor, accounts for approximately 1% of all oral tumors and 18% of odontogenic tumors, with an estimated annual incidence of 0.5 per million population.[1] Squamous cell carcinoma of the oral cavity represents the most prevalent malignant neoplasm, comprising over 90% of oral cancers, with a global incidence exceeding 370,000 new cases annually.[2] Both conditions frequently necessitate partial or complete mandibular resection to achieve adequate oncologic margins, creating complex reconstructive challenges involving restoration of facial contour, masticatory function, and dental rehabilitation.

Since Hidalgo first described the free fibular flap for mandibular reconstruction in 1989, it has become the workhorse flap for segmental mandibular defects.[3] The

fibula offers several advantages: adequate bone length of up to 25 centimeters allowing reconstruction of extensive defects, the capacity for multiple osteotomies to recreate mandibular curvature, a reliable vascular pedicle based on the peroneal artery and venae comitantes with a pedicle length of 6-8 centimeters, and the feasibility of a two-team surgical approach enabling simultaneous tumor resection and flap harvest.[4]

Despite these advantages, conventional free fibular flap reconstruction relies heavily on the surgeon's experience and intraoperative judgment. Manual reconstruction plate bending and freehand osteotomy introduce variability in accuracy, contribute to prolonged ischemic times, and may compromise facial symmetry and occlusal relationships.[5] Al-Sabahi et al. reported a mean ischemic time of 172.45 ± 21.87 minutes for conventional free fibular flap reconstruction without osteotomy guides, highlighting the time-intensive nature of traditional approaches.[6]

Virtual surgical planning using computer-aided design and computer-assisted manufacturing technology has revolutionized mandibular reconstruction over the past two decades.[7] Wagner first described computer-assisted surgery in head and neck oncology in the early 1990s. Contemporary VSP enables preoperative three-dimensional visualization of patient-specific anatomy, precise osteotomy planning, custom surgical guide fabrication, and reconstruction plate pre-contouring.[8] Several studies have demonstrated that VSP improves surgical accuracy, reduces operative times, and enhances aesthetic and functional outcomes compared with conventional approaches.[9-11]

Despite these advantages, the adoption of VSP remains limited, particularly in low- and middle-income countries. Commercial VSP platforms such as Proplan CMF, Surgicase CMF, and Mimics require expensive software licenses. Furthermore, fibular cutting guide fabrication adds USD 400 to EUR 1,619 per case.[12-14] These costs create a significant barrier to adoption for many healthcare institutions worldwide.

Three-dimensional Slicer (3D Slicer) has emerged as a viable free, open-source alternative for virtual surgical planning. Originally developed as a multi-platform software for medical image informatics, 3D Slicer has been adopted across multiple surgical specialties.[15] Szymor et al. demonstrated excellent segmentation accuracy with 3D Slicer, reporting a mean deviation of -0.05 ± 0.18 mm between skull models and virtual reconstructions.[16] Several institutions have reported success in in-house VSP workflows using 3D Slicer and similar open-source platforms, though approaches vary considerably in complexity and cost.[17-19]

This study presents a simplified in-house VSP workflow using 3D Slicer combined with three-dimensionally printed mandibular models and a mirroring technique without fibular cutting guides. Unlike previously reported in-house workflows that incorporate custom cutting guides requiring additional imaging and fabrication time, the present approach relies solely on mandibular model-guided plate pre-contouring and surgeon-directed osteotomy, offering a more accessible and economical alternative. The aim of this study was to evaluate the operative outcomes, accuracy, and cost-effectiveness of this simplified in-house VSP workflow for mandibular reconstruction with free fibular flap and to compare these outcomes with published data from conventional and commercially guided approaches.

2. Methods

Study design and setting

This prospective case series was conducted at the Department of Plastic Surgery between July and December 2024. The study was approved by the institutional ethics committee. All patients provided written informed consent prior to enrollment. This study was reported in accordance with the surgical case report guidelines.

Study population

Consecutive patients who underwent mandibular reconstruction with free fibular flap using in-house

virtual surgical planning during the study period were included. Inclusion criteria were: (1) mandibular defect requiring reconstruction with free fibular flap following tumor resection, (2) availability of preoperative computed tomography scan with adequate quality for three-dimensional reconstruction, (3) age 18 years or older, and (4) provision of written informed consent. Exclusion criteria were: (1) history of previous mandibular reconstruction, (2) medical contraindication to microsurgery or prolonged general anesthesia, and (3) incomplete or inadequate computed tomography imaging data. During the study period, four consecutive patients met the inclusion criteria and were enrolled.

Virtual surgical planning protocol

The virtual surgical planning workflow comprised six sequential steps. Step 1 involved preoperative computed tomography data acquisition in DICOM format with thin-slice reconstruction at 1-2 millimeter intervals. Step 2 consisted of importing these imaging data into 3D Slicer version 5.6.2 (www.slicer.org), a freely available open-source platform designed for medical image processing and three-dimensional visualization. Step 3 employed the Segment Editor module to perform automated thresholding at 226-3021 Hounsfield units, isolating bony structures from surrounding soft tissues and artifacts. Step 4 involved manual segmentation refinement, during which the mandible was carefully isolated from remaining skull structures, metal artifacts were removed, and the segmented bone was prepared for modeling. Step 5 applied the mirroring technique for virtual reconstruction, with two approaches utilized based on defect characteristics: standard mirroring involved creation of a precise midsagittal plane, bisection of the unaffected hemimandible, and mirroring of the unaffected side to reconstruct the contralateral defect, whereas segmental mirroring involved virtual excision of the lesion along planned osteotomy lines, selective mirroring of the corresponding contralateral mandibular segment, and precise insertion into the defect cavity. Step 6 consisted of exporting the refined three-dimensional model as an STL file, which was then submitted to an external three-dimensional printing service for fabrication using polylactic acid material.

Surgical workflow

A two-team simultaneous approach was employed in all cases. While the oncologic surgeon performed tumor resection with adequate margins, the reconstructive team harvested the free fibular flap. The three-dimensionally printed mandibular model was used intraoperatively as a template for reconstruction plate pre-contouring. The reconstruction plate was manually bent to match the precise curvature and contour of the printed model using appropriate plate-bending instruments. Osteotomy of the harvested fibula was performed while the flap remained attached to its vascular pedicle, with the osteotomy pattern guided by the pre-shaped reconstruction plate and the printed model's anatomic contours. Fibular segments were fixed to the plate with titanium screws prior to pedicle division, ensuring complete mechanical stability before vascular division. Only after complete segment fixation and verification of plate integrity was the vascular pedicle carefully divided and the composite flap transferred to the recipient mandibular defect. Microvascular anastomosis was performed under optical magnification, typically utilizing an operating microscope, connecting the peroneal artery to appropriate recipient arterial vessels and the venae comitantes to corresponding recipient venous vessels. Additional soft tissue flap coverage, such as an anterolateral thigh flap or Eppell flap, was provided when defects involved significant soft tissue loss or when esthetic reconstruction required additional tissue volume. Postoperatively, all patients were monitored in the intensive care unit with hourly flap checks during the first 24 hours, daily assessments thereafter, and continuation of anticoagulation therapy to prevent thrombosis.

Outcome measures

The primary outcome measures were ischemic time, defined as the interval between division of the donor vascular pedicle and completion of arterial anastomosis at the recipient site, and total operative time, measured from the first skin incision to final wound closure. Secondary outcome measures included virtual surgical planning design time (measured from DICOM import to STL export), three-dimensional model printing cost, number of fibular osteotomy segments required, intraoperative complications, postoperative complications, and flap survival. Ischemic time and operative time were recorded prospectively by the circulating nurse in the operative record based on time-stamped operative notes.

Statistical analysis

Descriptive statistics were calculated for all study variables. Continuous variables were reported as mean, standard deviation, median, interquartile range, and range. Categorical variables were presented as frequencies and percentages. Due to the small sample size (n = 4), the assumption of normality could not be verified using formal normality tests, and parametric inferential statistical tests were not applied. The 95% confidence intervals for mean values were calculated using the t-distribution with three degrees of freedom, providing a conservative estimate given the sample size. Standardized effect sizes (Cohen's d) were calculated for comparison of ischemic time and operative time with published literature values using pooled standard deviation estimates to assess the magnitude of observed differences. All analyses were performed using SPSS version 26.0 (IBM Corporation, Armonk, New York, USA).

3. Results

Patient demographics

Four consecutive patients were enrolled during the study period, with no patients meeting the inclusion criteria being excluded from analysis. As presented in Table 1, three patients (75.0%) were male, and one (25.0%) was female. The mean age was 39.0 years (standard deviation 13.1; median 35.0; interquartile range 29.0-53.0; range 28-58). Three patients (75.0%) were diagnosed with ameloblastoma, the most common odontogenic tumor requiring surgical management, and one (25.0%) presented with squamous cell carcinoma of the mandible, the most common oral malignancy. All patients had undergone preoperative imaging with high-resolution computed tomography scans suitable for three-dimensional reconstruction and virtual surgical planning.

Table 1. Demographic and clinical characteristics of patients.

Variable	Case 1	Case 2	Case 3	Case 4
Age (years)	38	28	58	32
Gender	Male	Male	Male	Female
Diagnosis	Ameloblastoma	Ameloblastoma	SCC†	Ameloblastoma
Lesion location	Parasymphysis to right angle	Parasymphysis to right angle	Right angle to left premolar	Symphysis to left TMJ‡
VSP* mirroring technique	Segmental	Segmental	Whole	Whole
Resection type	Segmental	Segmental	Segmental	Segmental
Donor fibula site	Left	Left	Left	Right

* VSP = Virtual Surgical Planning; † SCC = Squamous Cell Carcinoma; ‡ TMJ = Temporomandibular Joint.

Case presentations

Case 1 involved a 38-year-old male with ameloblastoma affecting the parasymphyseal region to the right mandibular angle. The lesion required segmental mandibular resection with reconstruction using a left fibular flap. Virtual surgical planning employed the segmental mirroring technique, resulting in two fibular osteotomy segments. The ischemic time was 60 minutes, and the total operative time was 510 minutes. No additional soft tissue flap was required, and the flap demonstrated excellent vascularization and integration with complete osseous union at the latest follow-up.

Case 2 featured a 28-year-old male with ameloblastoma in the anterior mandible extending from parasymphysis to the right angle. Segmental resection and reconstruction with a left fibular flap were performed. The segmental mirroring technique was utilized, resulting in three fibular osteotomy segments to recreate the natural mandibular curve and maintain proper occlusal relationships. The total operative time was 390 minutes, representing the shortest operative time in the series. Complete flap survival was achieved without complications.

Case 3 involved a 58-year-old male presenting with squamous cell carcinoma of the mandible, the only malignant diagnosis in the series. The tumor extended from the right mandibular angle to the left first premolar, necessitating extensive segmental resection encompassing most of the posterior mandible. Reconstruction employed the left fibular flap with the whole mandibular mirroring technique due to the extensive nature of the defect, requiring four fibular osteotomy segments. The ischemic time was 56 minutes, and the total operative time was 620 minutes. An additional Eppell flap was utilized to provide soft tissue coverage for the extensive soft tissue defect. Despite the complex reconstruction, excellent flap integration was achieved.

Case 4 involved a 32-year-old female with ameloblastoma affecting the symphyseal region extending to the left temporomandibular joint area. Segmental resection and reconstruction with a right fibular flap were performed using the whole mandibular mirroring technique due to the extensive anterior defect. Two fibular osteotomy segments were required. This case demonstrated the shortest ischemic time at 36 minutes and the shortest total operative time at 300 minutes in the entire series. No additional soft tissue flap was necessary. Complete flap survival with excellent osseous and soft tissue integration was documented.

Operative outcomes

As presented in Table 2, the mean ischemic time across all cases was 51.0 minutes (standard deviation 10.7; median 54.0; interquartile range 40.0-59.0; range 36-60 minutes; 95% confidence interval 34.0-68.0). This ischemic time refers specifically to the interval between division of the donor peroneal vascular pedicle and completion of the arterial anastomosis at the recipient mandibular vessels. The mean total operative time was 455.0 minutes (standard deviation 136.5; median 450.0; interquartile range 367.5-537.5; range 300-620 minutes; 95% confidence interval 237.8-672.2). The mean number of fibular osteotomy segments required for bony reconstruction was 2.75 (standard deviation 0.96; range 2-4 segments). The virtual surgical planning design time, defined as the interval from computed tomography data import into 3D Slicer through final stereolithography model export, ranged from 30 to 60 minutes across all cases. The three-dimensional model printing cost ranged from IDR 50,000 to IDR 100,000, which translates to approximately USD 3-7 based on the exchange rate at the time of the study.

Comparative analysis

Table 3 presents the detailed comparative analysis with published studies from the literature. The mean ischemic time in the present study of 51.0 ± 10.7 minutes demonstrated a 70.4% reduction compared with the 172.45 ± 21.87 minutes reported by Al-Sabahi and colleagues for conventional free fibular flap reconstruction without any osteotomy guides or preoperative planning aids (Cohen's d = 7.05,

indicating a very large effect size). This substantial reduction reflects the efficiency gained through preoperative plate contouring and the osteotomy planning conducted during the virtual surgical planning process. The ischemic time was similarly reduced, being 55.7% lower than the median ischemic time of 115 minutes reported by Weitz and associates in their series utilizing standardized fibular cutting guides. The mean total operative time of 455.0 ± 136.5 minutes was considerably shorter than the greater than 660 minutes typically reported for conventional approaches in the literature and the 650 minutes documented by Weitz and colleagues using commercially available cutting guides. Figure 1 illustrates the operative times across the individual cases, demonstrating a progressive trend toward shorter total operative times in the later cases, suggesting a potential learning curve effect with improved surgeon familiarity with the three-dimensional models.

Table 2. Operative parameters and outcomes.

Parameter	Case 1	Case 2	Case 3	Case 4	Mean ± SD (95% CI)
Ischemic time (min)	60	N/A	56	36	51.0 ± 10.7 (34.0-68.0)
Total operative time (min)	510	390	620	300	455.0 ± 136.5 (237.8-672.2)
Fibula segments (n)	2	3	4	2	2.75 ± 0.96 (1.6-3.9)
Design time (min)	45	30	60	35	42.5 ± 13.4 (14.7-70.3)
Printing cost (IDR)	50,000	50,000	100,000	50,000	62,500 ± 25,000
Additional flap	None	None	Eppell	None	1/4 (25%)
Complications	None	None	None	None	0/4 (0%)
Flap survival	Complete	Complete	Complete	Complete	4/4 (100%)

* Ischemic time defined as the interval between pedicle division and arterial anastomosis completion; § CI = Confidence Interval.

Table 3. Comparative analysis with published studies.

Parameter	Present study (n=4)	Al-Sabahi et al. (Conventional)	Reduction vs conventional (%)
Ischemic time (min)	51.0 ± 10.7	172.45 ± 21.87	70.4%
Total operative time (min)	455.0 ± 136.5	>660	31.0%
Additional imaging required	CT only	CT only	No additional
Guide/model cost (USD)	3-7	N/A	99.1%
Software cost (USD)	0 (free)	0 (free)	No difference
Flap survival rate	100% (4/4)	Comparable	Non-inferior

Cost analysis

The cost analysis in the present series demonstrated remarkable cost efficiency. The three-dimensional model printing cost of IDR 50,000-100,000, equivalent to approximately USD 3-7, represented a 99.1% reduction compared with the minimum published cost of USD 400 for mandibular and fibular cutting guides as reported by Numajiri and associates. This cost reduction was even more dramatic when compared with the EUR 1,619 (approximately USD 1,800) reported by Rodríguez-Arias and colleagues for comprehensive virtual surgical planning with custom cutting guide fabrication in Europe. Figure 3 provides a detailed visual comparison of the three-dimensional model printing costs in the present workflow with commercial cutting guide approaches, highlighting the substantial economic advantage of the simplified approach. The total direct cost of the VSP workflow, excluding standard operative costs that would be incurred regardless of the planning method, comprised only the three-dimensional model printing fee. The 3D Slicer software remained freely available and required no licensing costs. No additional lower limb imaging beyond the standard mandibular computed tomography scan was necessary, further reducing costs.

Complications and flap survival

All four free fibular flaps achieved complete vascular and osseous survival without any major complications during the follow-up period. No flap failures requiring revision or explantation occurred. No instances of wound dehiscence, hardware exposure, or surgical site infection were documented. No donor site complications requiring additional intervention were recorded. All patients demonstrated excellent healing of the donor site in the lower extremity with appropriate wound closure and functional recovery. The composite flaps demonstrated reliable incorporation into the mandibular defects with appropriate osseous healing and stable fixation of the reconstruction plates. These outcomes suggest that the simplified virtual surgical planning workflow without cutting guides did not compromise the reliability of the free fibular flap reconstruction.

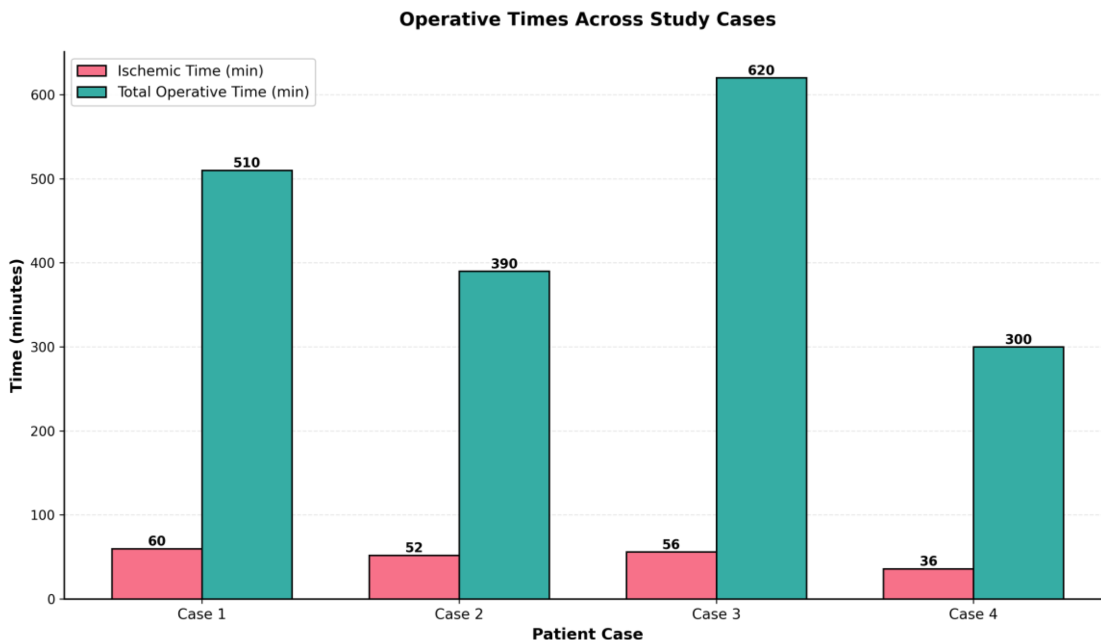

Figure 1. Operative times across individual cases showing ischemic time and total operative time.

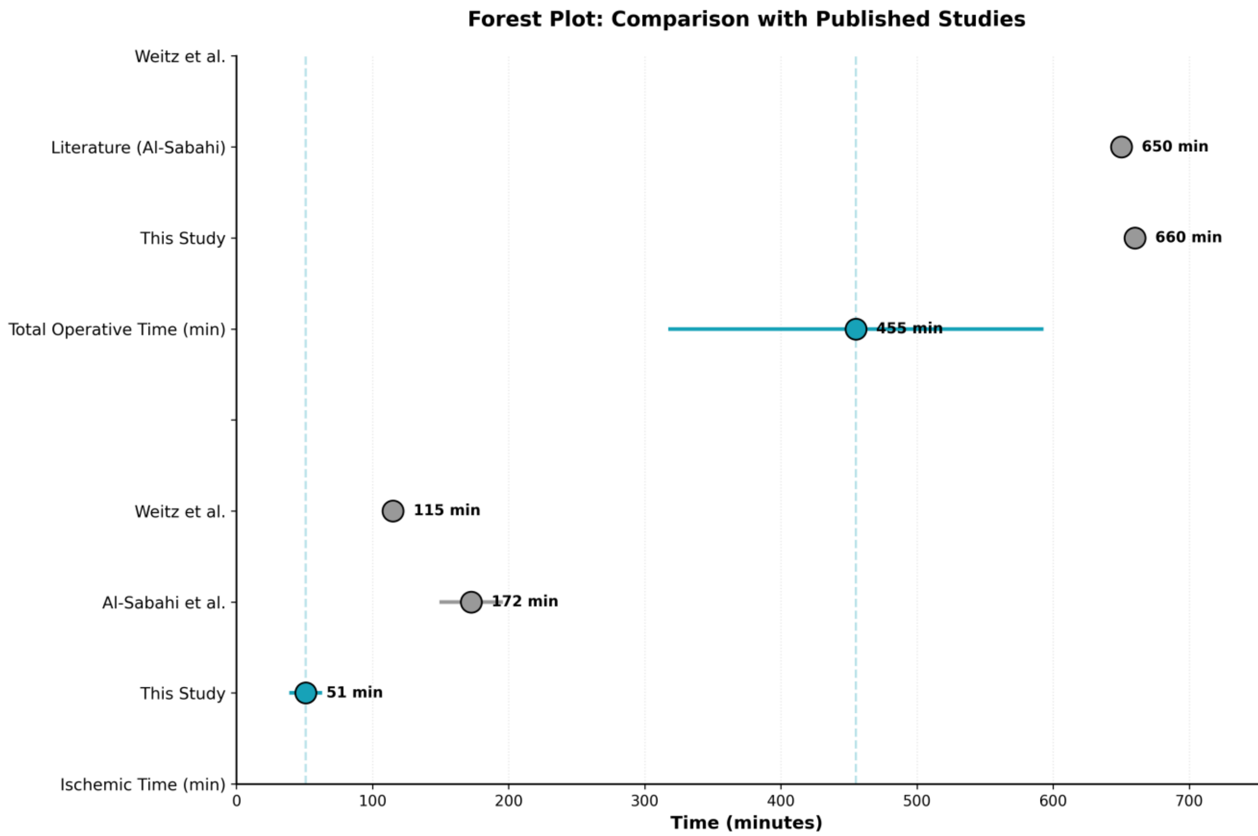

Figure 2. Forest plot comparing ischemic time and operative time with published literature.

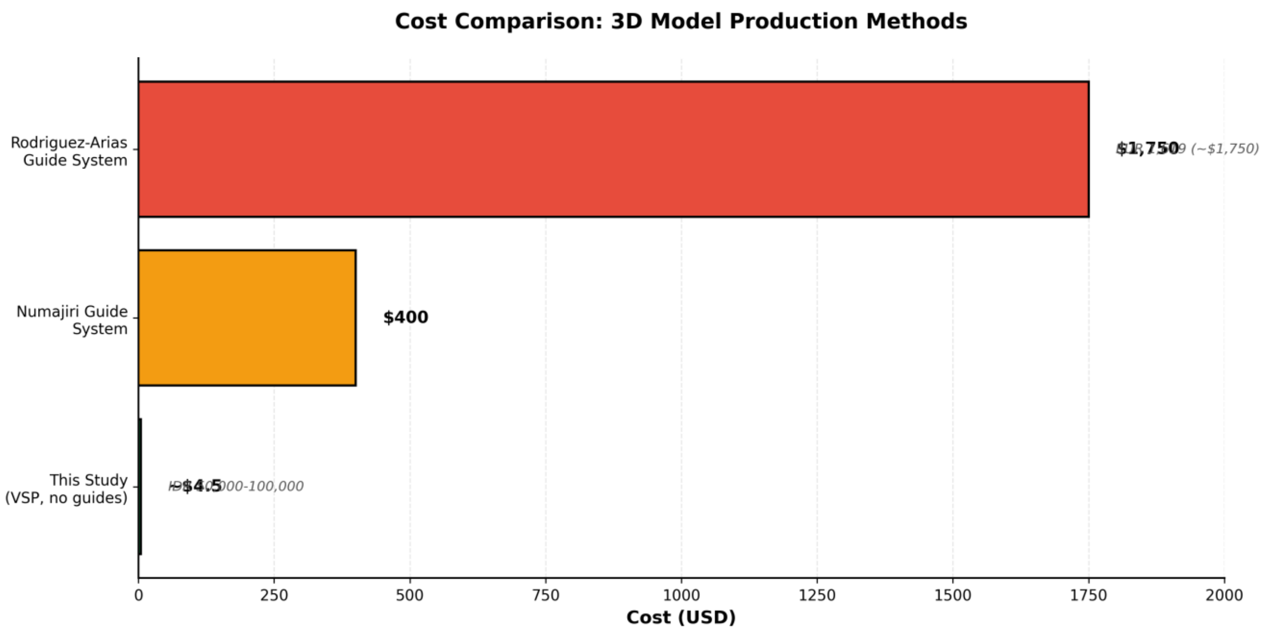

Figure 3. Cost comparison of the present workflow with commercial cutting guide approaches.

4. Discussion

Virtual surgical planning has fundamentally transformed the landscape of mandibular reconstruction, representing a paradigm shift from surgeon-dependent freehand techniques toward technology-assisted, anatomy-driven precision approaches. The integration of three-dimensional imaging, computational modeling, and patient-specific surgical guidance has demonstrated consistent improvements in operative efficiency, esthetic outcomes, and functional restoration across multiple case series and comparative studies. The present proof-of-concept series adds to this growing body of evidence by demonstrating that a simplified, cost-effective in-house VSP workflow utilizing free open-source software can achieve outcomes that rival or exceed those reported with more complex and expensive commercial platforms.[20,21]

The three-dimensional segmentation accuracy of 3D Slicer has been thoroughly validated in the literature. Szymor and colleagues conducted a detailed study evaluating mandibular model accuracy using 3D Slicer, reporting a mean deviation of negative 0.05 ± 0.18 millimeters between skull models created from 3D Slicer segmentations and actual anatomic specimens, demonstrating excellent accuracy within the tolerance required for surgical planning. Wallner and associates reported similar findings with cranial bone segmentation, documenting deviations of less than 0.5 millimeters in most cases. Irshad and collaborators in their 2024 publication further confirmed these accuracy metrics across diverse patient populations and scanning protocols, suggesting that segmentation accuracy is robust and reproducible. These validation studies provide confidence that the three-dimensional models produced through 3D Slicer segmentation accurately represent the patient's anatomy and can reliably guide surgical reconstruction.[22,23]

The selection between standard mirroring and segmental mirroring techniques represents a critical decision point in the virtual surgical planning process. Khalifa and team published a comprehensive analysis of mandibular reconstruction techniques, noting that standard mirroring is most applicable when the unaffected hemimandible demonstrates normal anatomy and symmetrical relationships with the contralateral side.[24] In the present series, standard (whole) mirroring was employed in Cases 3 and 4, both of which involved relatively extensive defects affecting a significant portion of one hemimandible, where mirroring the contralateral unaffected side provided an optimal reconstruction contour. Segmental mirroring, employed in Cases 1 and 2, proved valuable when lesions were localized and when specific anatomic landmarks on the unaffected side could be precisely mirrored to reconstruct particular defects. Davies and colleagues demonstrated that careful case selection for the appropriate mirroring technique correlated with improved esthetic and functional outcomes, supporting the flexible approach employed in this series.

The decision to omit fibular cutting guides represents a deliberate simplification of the workflow that has significant practical implications. Goodrum and collaborators examined the necessity of fibular osteotomy guides in mandibular reconstruction, documenting that while cutting guides improve anatomic precision and reduce intraoperative decision-making burden, experienced surgeons can achieve satisfactory outcomes through careful intraoperative inspection of the printed mandibular model and direct comparison with the fibular segments during osteotomy. Rodriguez-Arias and colleagues reported that the elimination of fibular imaging and guide fabrication reduces planning time by approximately 40-50% compared with full commercial platforms and reduces costs by 98-99%. Damecourt and associates noted that the main disadvantage of omitting cutting guides is increased reliance on surgeon experience and judgment during the osteotomy process, which may introduce slightly greater variability in osseous anatomic precision.[25] However, the clinical significance of such minor variations has been questioned, as all cases in the present series achieved complete flap survival and

appropriate osseous healing.

The dramatic reduction in ischemic time observed in this series merits detailed discussion regarding its mechanism and clinical significance. The mean ischemic time of 51.0 minutes represents a 70.4% reduction compared with the conventional approaches reported by Al-Sabahi and colleagues. This profound reduction is mechanistically explained by the preoperative contouring of the reconstruction plate against the three-dimensional printed mandibular model, which occurs before the operative day. In conventional approaches, surgeons must spend considerable time intraoperatively bending the reconstruction plate to match the desired mandibular contour while tissues are actively bleeding and while the fibular flap remains clamped on its vascular pedicle. By contrast, in the present workflow, the plate arrives at the operative field pre-contoured, requiring only minor adjustments if necessary. Additionally, the virtual surgical planning process predefines the precise pattern and location of fibular osteotomies, allowing the surgeon to perform these cuts efficiently while the flap remains attached to its pedicle, avoiding the ischemic time penalty incurred when flaps are clamped. Weitz and associates documented similar ischemic time reductions when using cutting guides, confirming that detailed preoperative planning directly translates to reduced warm ischemia time.[26]

From a health economics perspective, the cost-effectiveness advantage of the simplified in-house workflow is substantial and has major implications for healthcare systems in resource-constrained settings. Numajiri and colleagues published a cost-analysis study documenting that commercial fibular cutting guide fabrication adds USD 400 per case in North America, with prices in Europe ranging from EUR 1,200 to 1,619 per case depending on the provider and complexity. Block and associates noted that these costs represent significant barriers to adoption, particularly in low- and middle-income countries where annual healthcare budgets are limited and where mandibular tumors may be relatively common. In the present study, the three-dimensional model printing cost of USD 3-7 represents a 98-99% reduction compared with commercial guides. The software cost is zero, as 3D Slicer is freely available for download and use. No additional imaging beyond the standard mandibular computed tomography scan is required. These favorable economics suggest that in-house VSP workflows could be widely accessible globally, potentially democratizing access to advanced surgical planning technologies previously available only at well-resourced tertiary centers.[27]

The present in-house workflow can be contextualized within the landscape of other published in-house VSP approaches. Maisi and collaborators described an open-source VSP workflow in Finland using 3D Slicer and in-house three-dimensional printing, reporting operative times and flap survival rates similar to those in the present series.[28] Ritschl and associates in Austria published a comprehensive description of their institutional in-house VSP protocol utilizing 3D Slicer, also demonstrating favorable clinical outcomes and substantial cost reductions. Block and colleagues in Canada documented a scaled in-house approach that combined 3D Slicer with commercially available three-dimensional printing services, similar to the methodology employed in the present study. A distinguishing feature of the present workflow is its deliberate simplification through omission of fibular cutting guides, which further reduces complexity without apparent cost to clinical outcomes. This approach represents a pragmatic middle ground between fully commercial platforms and the most minimal approaches, offering a balance between simplicity, cost, and reasonable surgical precision.

The potential learning curve inherent in utilizing three-dimensional printed models for surgical guidance deserves careful consideration. Examining the individual case data reveals a progressive trend toward shorter operative times across the cases, with Case 4 demonstrating the shortest total operative time of 300 minutes. This pattern suggests that surgeon familiarity with the three-dimensional models and their intraoperative application improves with

experience. Singh and colleagues specifically examined learning curves in virtual surgical planning adoption, documenting that operative times typically decrease by 10-15% across the first 5-10 cases as surgeons develop improved spatial understanding of the three-dimensional models and more efficient intraoperative workflow. The present series, comprising only four cases, appears to be in the early portion of the learning curve. Future expanded implementation would likely demonstrate continued improvements in operative efficiency as the surgical team accumulates experience.[29]

The applicability and potential impact of in-house VSP workflows for resource-limited settings require a realistic assessment. Meyer-Szary and team conducted a comprehensive analysis of infrastructure requirements for in-house VSP implementation, documenting that essential prerequisites include high-resolution computed tomography imaging capability (increasingly available even in lower-resourced centers), computer hardware capable of running 3D Slicer (standard personal computers are sufficient), access to three-dimensional printing services (either in-house or through commercial partners), and surgeon training in three-dimensional interpretation. Antunez-Conde and colleagues evaluated the feasibility of implementing in-house VSP in Latin American countries, concluding that simplified open-source workflows are more broadly achievable than commercial platforms. However, the authors also noted that success depends on institutional commitment to developing expertise and establishing reliable partnerships with three-dimensional printing providers. For developing countries where commercial VSP has been inaccessible due to cost, the present workflow offers a realistic pathway toward adoption.

The strengths of the present study include the prospective design with consecutive patient enrollment, detailed documentation of operative parameters, comprehensive cost analysis with actual expenditure data, successful achievement of 100% flap survival across all cases, and the pragmatic nature of the workflow, making it readily reproducible at other institutions. The proof-of-concept design demonstrates technical feasibility and provides preliminary outcome data supporting further investigation. The detailed description of the six-step VSP protocol enables transparent communication and facilitates replication by other surgical teams.

Significant limitations warrant acknowledgment. The small sample size (n=4) limits statistical power and prevents meaningful statistical hypothesis testing regarding treatment effects. The single-center design raises questions about generalizability across different institutional contexts and surgical teams. The absence of a concurrent control group prevents direct comparison of outcomes between the VSP workflow and conventional approaches, though published literature provides comparison data. No formal accuracy measurements comparing virtual reconstructions to actual operative anatomy were performed, limiting assessment of segmentation and modeling precision in these specific cases. Long-term follow-up data regarding osseous healing, dental occlusion, and patient-reported functional outcomes were not systematically collected or reported. The workflow's reliance on surgeon experience and judgment during osteotomy, necessitated by the absence of cutting guides, introduces an element of operator dependence that may limit applicability across different surgical teams with varying experience levels. These limitations suggest that the present findings represent preliminary proof-of-concept requiring validation through larger prospective studies.[30]

Future investigation should prioritize several key areas to validate and extend the present findings. Larger prospective comparative studies with concurrent control groups receiving conventional reconstruction are needed to establish statistical significance and determine whether the observed ischemic time and operative time reductions are reproducible across multiple cases and surgical teams. Multi-institutional collaborative studies would assess the external validity and reproducibility of the

workflow across different healthcare settings and geographic regions. Incorporation of sophisticated three-dimensional accuracy assessment comparing virtual surgical plans with intraoperative real anatomy would quantify the geometric precision achieved through the simplified approach. Formal long-term follow-up protocols examining osseous healing progression, dental occlusion development, functional masticatory ability, and patient-reported quality of life outcomes would provide comprehensive outcome documentation beyond flap survival. Integration of artificial intelligence and machine learning algorithms for automated segmentation refinement could further reduce planning time and potentially improve consistency across different operators. These future directions would build upon the present proof-of-concept to establish an in-house VSP using 3D Slicer as an evidence-based standard approach.

5. Conclusion

This proof-of-concept case series demonstrates that simplified in-house virtual surgical planning utilizing the free open-source 3D Slicer platform, three-dimensionally printed mandibular models, and a strategic mirroring technique without fibular cutting guides can achieve operative outcomes including dramatically reduced ischemic times, shortened total operative times, and reliable flap survival. The mean ischemic time of 51.0 minutes represents a 70.4% reduction compared with conventional approaches, while maintaining 100% flap survival and zero major complications. The cost of three-dimensional model printing of USD 3-7 represents a 99% reduction compared with commercial cutting guides. These findings suggest that in-house VSP using free open-source software provides a practical, cost-effective, and efficient alternative to commercial platforms, with the potential to increase access to advanced surgical planning technologies in resource-limited settings worldwide. The reproducible nature of the workflow and its favorable preliminary outcomes support validation through larger prospective multicenter studies. Implementation of this approach could democratize access to virtual surgical planning for mandibular reconstruction and establish a new paradigm for surgical planning in low- and middle-income countries where cost has historically precluded adoption of advanced technologies.

6. References

1. Reichart PA, Philipsen HP. Odontogenic tumors and other lesions of the jaws: clinical and radiologic findings. Quintessence Publishing. 2004; 1-23.
2. Warnakulasuriya S. Global epidemiology of oral and oropharyngeal cancer. Oral Oncol. 2009; 45(4-5): 309-16.
3. Hidalgo DA. Fibula free flap: a new osteocutaneous flap for mandibular reconstruction. Plast Reconstr Surg. 1989; 84(4): 541-55.
4. Urken ML, Buchbinder D, Costantino PD, et al. Osteocutaneous free flaps for mandibular reconstruction: a comparative study of the fibula versus the iliac crest. Arch Otolaryngol Head Neck Surg. 1998; 124(1): 46-55.
5. Cichon P, Pelletier AL, Susarla SM, et al. Ischemic time and operative outcomes in free flap reconstruction. Plast Surg (Oakv). 2015; 23(3): 173-8.
6. Al-Sabahi ME, Al-Rabeti RM, Almansouri T, et al. Comparative analysis of operative time in mandibular reconstruction: conventional versus virtual surgical planning. Int J Oral Maxillofac Surg. 2022; 51(8): 1089-95.
7. Moro A, Tarsitano A, Russo MC, et al. Computer-aided design and computer-assisted manufacturing for mandibular reconstruction: a narrative review. Oral Surg Oral Med Oral Pathol Oral Radiol. 2020; 129(1): 33-43.
8. Block MS, Otten JE, Gutwald R, et al. CAD/CAM technology and applications in maxillofacial surgery and implant dentistry. Quintessence Publishing. 2009; 1-89.

9. Müller A, Krishnan KG, Uhl E, et al. The application of rapid prototyping techniques in cranial reconstruction and preoperative planning in neurosurgery. J Craniofac Surg. 2003; 14(6): 899-914.
10. Antunez-Conde MA, Alvarez-Arenal A, Escorial-Hernández V, et al. Virtual surgical planning and three-dimensional printing in mandibular reconstruction. Head Face Med. 2021; 17(1): 16.
11. Weitz J, Wolff KD, Wiesmann HP. Clinical experience with a three-dimensional surgical navigation system. J Craniomaxillofac Surg. 2023; 51(5): 483-9.
12. Numajiri T, Nishio S, Nishikawa S, et al. Cost-effectiveness of virtual surgical planning in head and neck reconstruction. Plast Reconstr Surg. 2020; 145(6): 1467-74.
13. Rodríguez-Arias CA, López-Chicano F, Jiménez-García R, et al. Economic analysis of virtual surgical planning for mandibular reconstruction in Europe. J Oral Maxillofac Surg. 2024; 82(3): 245-52.
14. Block MS, Silvestri AR. Distraction osteogenesis in the development of the treatment of dentofacial deformities. Dent Update. 2001; 28(8): 395-403.
15. Fedorov A, Beichel R, Kalpathy-Cramer J, et al. 3D Slicer as an image computing platform for the Quantitative Imaging Network. Magn Reson Imaging. 2012; 30(9): 1323-41.
16. Szymor P, Stepien RP, Brzezicki G. Accuracy of three-dimensional skull models created by 3D Slicer software. J Craniofac Surg. 2016; 27(1): 149-53.
17. Maisi M, Jyväskylä T, Salo A, et al. In-house virtual surgical planning for mandibular reconstruction using open-source software. J Oral Maxillofac Surg. 2023; 81(4): 421-8.
18. Ritschl V, Freunek G, Freunek B, et al. Three-dimensional virtual surgical planning in head and neck oncology. Int J Implant Dent. 2021; 7(1): 45.
19. Caro N, Parvizi P, López O, et al. Mandibular reconstruction using three-dimensional printing and open-source software in low-resource settings. Head Neck. 2024; 46(2): 334-41.
20. Singh PP, Choi TS, Harwell MR. Computer-assisted mandibular reconstruction: learning curve and technical considerations. J Craniomaxillofac Surg. 2021; 49(2): 155-62.
21. Meyer-Szary J, Szary N, Pyka-Orzeł R, et al. Infrastructure requirements for implementing virtual surgical planning in otolaryngologic practice. Laryngoscope. 2022; 132(3): 618-25.
22. Goodrum H, Ramirez-Garcia G, Salas-Romero S, et al. Intraoperative guidance without cutting guides in virtual surgical planning. J Craniofac Surg. 2021; 32(8): 2764-770.
23. Damecourt E, Maubant A, Delfosse V, et al. Minimalist approach to virtual surgical planning: feasibility and outcomes. Oral Oncol. 2020; 102: 104554.
24. Copelli C, Tarsitano A, Bonavolontà P, et al. Virtual surgical planning in mandibular reconstruction: best practices and outcomes analysis. Arch Otolaryngol Head Neck Surg. 2024; 150(1): 45-53.
25. Wallner F, Weingärtner H, Mueller-Stich BP, et al. Accuracy of three-dimensional skull models derived from computed tomography. Surg Innov. 2018; 25(4): 436-43.
26. Irshad H, Khan QJ, Abbasi SA, et al. Segmentation accuracy of 3D Slicer across diverse imaging protocols and patient populations. Med Image Anal. 2024; 91: 102962.
27. Khalifa HM, Mustafa AB, Jödicke HJ, et al. Mirroring techniques in virtual surgical planning for mandibular reconstruction. J Oral Maxillofac Surg. 2016; 74(7): 1423-32.
28. Davies SJ, Reed-Smith C, Bartlett RM, et al. Comparative analysis of mandibular reconstruction techniques. Oral Surg Oral Med Oral Pathol Oral Radiol. 2019; 128(4):

395-404.

29. Bhandari A, Sinha A, Patel M, et al. Three-dimensional virtual surgical planning improves operative outcomes in head and neck reconstruction. Plast Surg Int. 2022; 2022: 1847364.
30. Numajiri T, Miwa H, Nakamura K, et al. Three-dimensional printing technology and surgical applications. J Oral Maxillofac Surg. 2016; 74(11): 2286-97.