

Feasibility of Low-Cost In-House 3D Printing in Mandibular Reconstruction with Fibula Free Flap: Initial Regional Experience from Northern Thailand

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Abstract

Background: Computer-assisted mandibular reconstruction with fibula free flap (FFF) improves accuracy but is often limited by high cost and dependency on external engineering support. This study evaluated the feasibility, workflow, and outcomes of a low-cost, in-house 3D printing protocol for mandibular reconstruction in a regional hospital.

Materials and Methods: Eighteen patients who underwent in-house, open-source-based 3D-planned FFF reconstruction between 2020 and 2025 were retrospectively reviewed. We analyzed demographic, operative, and reconstructive parameters, including ischemia time, operative duration, flap survival, and postoperative outcomes.

Results: The mean age was 60.9 years, with an equal sex distribution. Squamous cell carcinoma was the most common diagnosis (61%), and lateral-type defects predominated (78%). All reconstructions used osteocutaneous FFF with a single skin paddle. The mean defect length was 83.8 mm, ischemia time was 101 ± 32 minutes, and total operative time was 613 ± 110 minutes. No patient required routine ICU admission. All 18 flaps survived (100%). Minor complications included two fistulae (11%) and one plate exposure (5.6%). The average 3D printing cost was approximately 100 THB (USD 2.7) per model.

Conclusion: An in-house, surgeon-driven 3D printing workflow using open-source software is feasible, accurate, and cost-effective for mandibular reconstruction. A regional hospital setting can achieve outcomes comparable to high-cost commercial systems, supporting broader access to digital reconstructive technology.

Keywords: Mandibular reconstruction, Fibula free flap, 3D printing, Open-source software, Virtual surgical planning, In-house workflow

INTRODUCTION

Mandibular defects are among the most challenging problems in head and neck reconstruction, as they affect both function and aesthetics by compromising mastication, speech, swallowing, airway, and facial contour.^{1,2} The fibula free flap, first described by Hidalgo in 1989, has since become the gold standard for mandibular reconstruction, owing to its reliable vascularity, sufficient bone length, and potential for multiple osteotomies.^{1,3} Despite its advantages, the procedure remains technically demanding,

especially when restoring mandibular continuity and symmetry in complex oncological or post-traumatic cases.

Over the past two decades, computer-assisted surgery (CAS) and computer-aided design and manufacturing (CAD/CAM) technologies have revolutionized maxillofacial reconstruction.⁴⁻⁶ Virtual surgical planning (VSP) enables precise preoperative design of osteotomies and reconstruction plates, improving accuracy, reducing ischemia time, and optimizing functional and esthetic outcomes.^{7,8} However, the widespread application of

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CAD/CAM-guided mandibular reconstruction has been limited by high costs, dependency on external engineering support, and time-consuming manufacturing processes.^{4,9} These barriers are especially critical in resource-limited or regional hospitals, where timely treatment is required for malignant conditions.

To overcome these challenges, several groups have explored low-cost, in-house, or open-source workflows for 3D surgical modeling and guide fabrication.¹⁰⁻¹³ Such strategies allow surgeons to independently perform virtual planning, design osteotomy guides, and print models or templates with affordable 3D printers. These methods have shown accuracy comparable to commercial systems while substantially reducing cost and turnaround time. Nonetheless, clinical data on the feasibility and outcomes of low-cost in-house 3D printing protocols, particularly in developing healthcare systems, remain scarce.

In this study, we present our initial regional experience with low-cost, in-house 3D printing for mandibular reconstruction using fibula free flaps in a tertiary referral hospital in Northern Thailand. We aimed to evaluate the feasibility, workflow, and clinical outcomes of this approach compared with traditional methods, emphasizing accessibility and applicability in resource-limited settings.

MATERIALS AND METHODS

Study design and setting

This retrospective cohort study was conducted at Lampang Hospital, a tertiary referral center in Northern Thailand. We reviewed all consecutive patients who underwent mandibular reconstruction using fibula free flap (FFF) between January 2019 and June 2025. We included reconstructed cases using the in-house 3D printing protocol to analyze workflow feasibility, technical aspects, and clinical outcomes. A single reconstructive surgeon (Dr. Thanyanan Panich T.P.) performed all operations, ensuring uniform surgical technique and workflow implementation throughout the study period.

Patient selection

Inclusion criteria

- Segmental mandibular defect requiring reconstruction with fibula osteocutaneous free flap
- Virtual planning and model fabrication performed with in-house 3D printing workflow
- Complete preoperative and postoperative imaging available

Exclusion criteria

- Incomplete records or non-fibular donor site
- Cases reconstructed without the 3D workflow

A total of 18 consecutive patients met the criteria and were included in the analysis.

Preoperative imaging and planning workflow

All patients underwent contrast-enhanced CT of the facial bones (1.0-1.25 mm slice thickness) for mandibular modeling. We obtained leg CT angiography in 15 patients (83%) to evaluate donor-site vascular anatomy. In the remaining three patients (17%), we did not perform preoperative CTA of the lower leg because CTA scheduling times exceeded the planned surgical dates. These patients required expedited surgery because of aggressive or advanced malignancies, in which further delay could have resulted in disease progression.

For these three cases without lower-extremity CTA, we derived fibular models from previously acquired CT datasets of other patients of the same sex with comparable anthropometric characteristics, including body habitus, height, and body mass index (BMI). We used these surrogate fibular models solely for virtual planning and in-house cutting guide design, rather than patient-specific fibular models, while intraoperative assessment of fibular anatomy and the vascular pedicle was performed in the standard manner. We converted DICOM data to STL format using 3D Slicer® and imported them into Blender® (open-source software, Amsterdam, Netherlands) to virtually design resection margins and osteotomies. We planned defect length, osteotomy angles, and segment configuration to restore mandibular continuity. We pre-bent each patient's reconstruction plate on a printed mandibular model before surgery.

The reconstruction plates used in this study were standard, commercially available mandibular reconstruction plates and were not customized or patient-specific implants. The operating surgeon manually pre-bent the plates using an in-house 3D-printed mandibular model. In cases involving segmental mandibular defects, the defect geometry on the printed model was reconstructed virtually by mirroring the contralateral intact mandible to restore the original mandibular contour. This mirrored mandibular model served as a reference for plate contouring and adaptation prior to surgery.

In-house 3D printing protocol

We fabricated three-dimensional mandibular models and cutting guides for the mandible and fibular flap entirely in-house using a desktop fused deposition modeling (FDM) 3D printer (Creality Ender series).

Printing parameters

- Material: Polylactic acid (PLA) filament
- Printing time: 1-10 hours per model

- Average cost: approximately 100 Thai Baht ($\approx$ USD 2.7) per model
- Sterilization: low-temperature hydrogen peroxide plasma system (STERRAD[®])

The surgical team performed all planning and model fabrication without outsourcing or external engineering support. This approach followed the principles of low-cost, surgeon-driven design previously described by Ganry L et al. (2017), Bosc et al. (2017), and Damecourt et al. (2020), adapted to a regional hospital setting (**Figure 1**).

Surgical technique

Mandibulectomy was performed using the mandibular cutting guide (**Figure 1**). Then the recipient vessels were identified.

Fibula osteocutaneous flaps were harvested based on the peroneal pedicle in all 18 cases (100%). Osteotomies were performed according to the printed fibular cutting guide. Then the segment of the fibular bone was rearranged and fixed to the remaining mandible with the pre-bent reconstruction plate.

(**Figure 2**). Microvascular anastomoses were performed to the facial or superior thyroid artery and appropriate venous branches under high magnification using a Zeiss Tivato 700 surgical microscope.

Soft-tissue paddles (mean 4×6 cm) were inset for intraoral lining or external coverage as indicated (**Figure 2**). A well-trained plastic scrub nurse and plastic assistant nurse team supported each operation and were familiar with microsurgical workflow.

Clinical photographs of three patients at 1-year follow-up after fibula free flap reconstruction. All patients demonstrated stable mandibular contour, complete soft-tissue healing, and good functional recovery; they tolerated a regular oral diet and achieved speech intelligibility scores of 4-5. These results illustrate the long-term aesthetic and functional reliability of the low-cost, in-house 3D-planning protocol.

Postoperative management

All patients were cared for in a dedicated plastic surgery ward, without routine intensive care unit (ICU) admission.

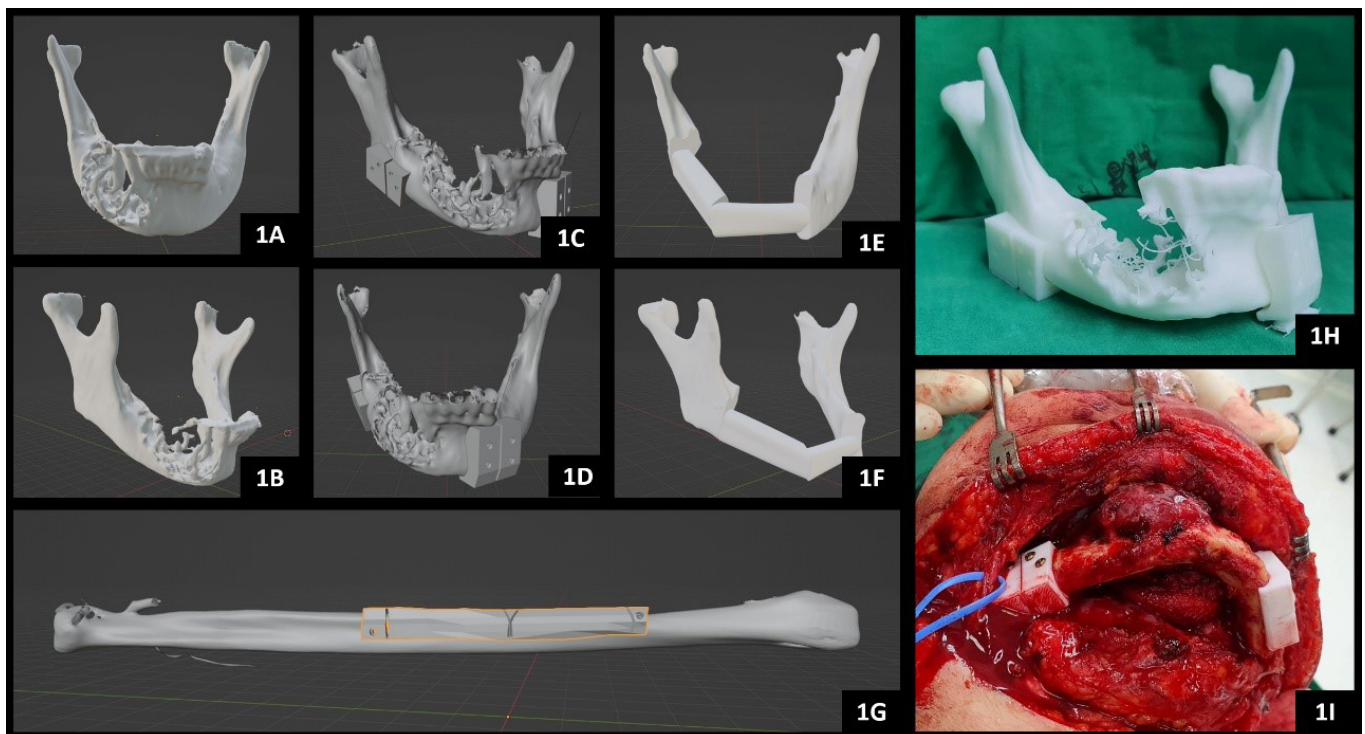


Figure 1 Virtual planning and in-house 3D printing workflow for mandibular reconstruction with fibula free flaps.

(1A, 1B) Three-dimensional mandibular models generated in Blender show tumor invasion involving the mandibular body and angle. (1C, 1D) Virtual simulation of mandibular osteotomy planning demonstrates the cutting planes prepared for intraoperative guidance. (1E, 1F) post-resection reconstruction planning illustrating complete tumor removal and replacement of the missing segment with a fibula free flap.

(1G) Virtual design of the fibular cutting guide based on the planned osteotomies.

(1H) The final 3D-printed surgical model and guide were fabricated in-house for intraoperative use.

(1I) Intraoperative view showing the practical application of the printed cutting guide during actual mandibular reconstruction. This figure illustrates the fully digital-to-surgical workflow of the low-cost, open-source 3D planning protocol used in this study.

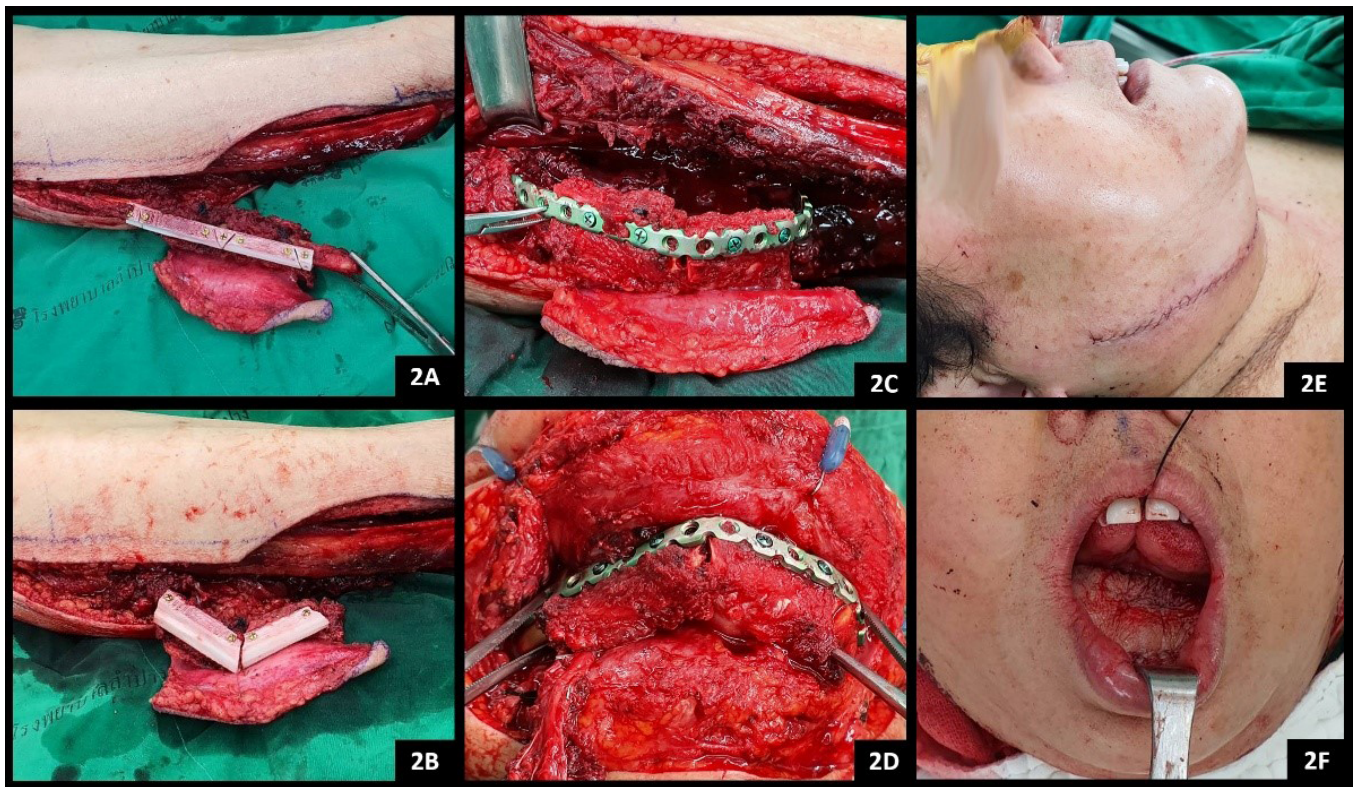


Figure 2 Intraoperative workflow of mandibular reconstruction using an in-house 3D-planned fibula free flap.

(A) Application of the printed cutting guide on the fibula with a skin paddle.

(B) After osteotomies, the fibular segments are aligned and shaped according to the predesigned mandibular template.

(C) Pre-bent reconstruction plate fitted onto the fibula flap with skin paddle before vascular division.

(D) Completed fixation of the fibula flap to the mandible, demonstrating precise alignment and excellent anatomical fit with the preoperative plan.

(E) Submental view after wound closure, showing an esthetically restored mandibular contour.

(F) Intraoral view of the skin paddle used for mucosal lining.

This figure illustrates the translation of the virtual plan into surgical execution, highlighting accuracy and contour restoration achieved through low-cost, in-house 3D planning.



Figure 3 Representative one-year postoperative outcomes following in-house 3D-planned mandibular reconstruction.

We monitored flaps hourly for the first 48 hours using clinical observation and Doppler signal assessment.

We followed institutional standards for antibiotic prophylaxis and anticoagulant regimens for free flap reconstruction. We encouraged early oral feeding and ambulation when tolerated.

Data collection and outcome measures

Collected variables included demographics, comorbidities, diagnosis, defect classification (Jewer), defect length, soft-tissue paddle size, imaging workflow, and pedicle usage.

Primary feasibility outcomes

- Success of model and guide fabrication
- Intraoperative accuracy of fit
- Operative and ischemia times (where available)

Secondary outcomes

- Perioperative complications
- Flap survival
- Postoperative course

Descriptive statistics were reported as mean $\pm$ standard deviation (SD) or percentage, as appropriate.

Ethical considerations

This study was approved by the Institutional Review Board of Lampang Hospital (IRB No. EC170/68). All patients provided written informed consent for surgical treatment and for the use of anonymized data and images for academic publication.

The study followed the Declaration of Helsinki (2013 revision).

RESULTS

Patient demographics and baseline characteristics

Eighteen patients underwent mandibular reconstruction using the in-house 3D-planned fibula free flap protocol at Lampang Hospital between 2020 and 2025. The mean age was 60.9 ± 18.1 years (range, 23-85), with an equal sex distribution (9 males and 9 females). Two-thirds of patients (67%) had at least one underlying comorbidity, most commonly hypertension (50%) and dyslipidemia (39%). The mean body mass index was 21.5 ± 4.7 kg/m². One-third of patients were active smokers, and six patients (33%) had no comorbidities. **Table 1** summarizes these baseline characteristics.

Table 1 Patient demographics and baseline characteristics

	Mean $\pm$ SD, n (%)	Range
Age	60.9 $\pm$ 18.1	23-85
Sex	Male 9 (50)	-
Height (cm)	157.3 $\pm$ 14.0	115-185
Weight (kg)	56.3 $\pm$ 17.7	36.3-114.0
BMI	21.5 $\pm$ 4.7	15.8-33.3
Smoking	6 (33)	-
Underlying disease	12 (67%) $\geq$ 1 comorbidity	-
HT	9 (50)	-
DLP	7 (39)	-
DM	1 (6)	-
Other	4 (22)	-
None	6 (33)	-

Table 1 summarizes the demographic and baseline characteristics of 18 patients who underwent mandibular reconstruction with an in-house 3D-planned fibula free flap at Lampang Hospital. The cohort had a mean age of 60.9 years (range, 23-85) with an equal sex distribution. Two-thirds of patients presented with at least one comorbidity, with hypertension being the most common (50%). The overall profile reflects a typical middle-aged oral cancer population, consistent with prior 3D-assisted reconstruction series.

Operative and reconstructive outcomes

The primary diagnosis was squamous cell carcinoma in 11 patients (61.1%), followed by benign lesions such as ameloblastoma in 5 (27.8%), one case of osteoradionecrosis, and one post-traumatic defect. Most defects were lateral-type according to the Jewer classification—L, LC, or LCL—comprising 14 of 18 cases (77.8%). Two patients (11.1%) had central (C) defects, and two had hemimandibular (H) defects. The mean defect length was 83.8 ± 20.7 mm (range, 50-135 mm). All reconstructions utilized osteocutaneous fibula free flaps with a single soft-tissue paddle; the mean paddle width and length were 38.2 ± 11.6 mm and 64.4 ± 22.8 mm, respectively.

We obtained preoperative CT facial bone imaging in all patients (100%) and performed CTA of the leg in 15 patients (83.3%). We used a peroneal pedicle in all 18 cases (100%). We performed three-dimensional surgical planning using Blender open-source software, and the average 3D printing cost was The mean cost of in-house 3D printing was 108.8 ± 16.0 THB per case (range, 80-150 THB; approximately USD 3.0), covering material costs for printing all mandibular and fibular models and the cutting guides required for each reconstruction. This cost did not include reconstruction plates or fixation screws.

The mean number of fibular osteotomies was 2.1 ± 0.7 (range, 1-3). The mean ischemia time was 101 ± 32 minutes, the mean flap operative time was 437 ± 76 minutes, and the total operative time was 613 ± 110 minutes. No routine post-operative ICU admission was required. The average hospital stay was 15.6 ± 4.8 days (range, 10-50). One patient (5.6%) required re-exploration for venous congestion, and all 18 flaps (100%) survived.

Minor complications included two intraoral fistulae (11.1%), one plate exposure (5.6%), and two donor-site wound dehiscences (11%), all of which healed with conservative management. At discharge, 15 patients (83%) tolerated a soft or blended diet and had excellent speech intelligibility (score 4-5). The mean total hospitalization cost was $244,410 \pm 88,497$ THB (range). All patients completed a minimum follow-up period of 6 months (range 6-60 months), at which time flap survival remained 100%.

Table 2 summarizes operative and reconstructive parameters.

Table 2 Operative and reconstructive characteristics

	n (%) or Mean ± SD	Range / Details
Main diagnosis		
Squamous cell CA	11 (61.1)	-
Ameloblastoma / Benign lesion	5 (27.8)	-
Osteoradionecrosis	1 (5.6)	-
Post-traumatic defect	1 (5.6)	-
Defect side		
Left	8 (44)	-
Right	6 (33)	-
Bilateral/Midline	4 (22)	-
B/J Classification		
L	5 (27)	-
LC	4 (22)	-
LCL	5 (27)	-
C	2 (11.1)	-
H	2 (11.1)	-
L-type (L, LC, LCL)	14 (77.8)	-
Defect length (mm)	83.8 ± 20.7	50-135
Soft tissue paddle usage	18 (100)	All osteocutaneous
Paddle width (mm)	38.2 ± 11.6	FFF
Paddle length (mm)	64.4 ± 22.8	20-60 30-110
Pre-op imaging		
CT facial bone	18 (100)	-
CTA leg	15 (83.3)	-
Peroneal pedicle used	18 (100)	-
3D printing cost per case	108.8 ± 16.0 THB (USD 3.0)	80-150
Peri-operative		
No Fibula osteotomies	2.1 ± 0.7	1-3
Ischemia time (min)	101 ± 32	60-165
Flap operative time (min)	437 ± 76	320-580
Total operative time (min)	613 ± 110	450-840
PRC transfusion (units)	0.7 ± 0.9	0-3
ICU stay (days)	0	0
Length of Stay (days)	15.6 ± 4.8	10-50
Post-operative		
Flap survival (6-month follow-up)	18 (100)	-
Re-exploration	1 (5.6)	-
Thrombosis	0	-
Fistula	2 (11.1)	-
Plate exposure	1 (5.6)	-
Donor site complication	2 (11)	-
Soft diet or BD at discharge	15 (83)	Minor wound dehiscence
Excellent Speech intelligibility (4-5)	15 (83)	-
Total Cost (THB)	244,410 ± 88,497	148,847-445,570

Abbreviations: CA, carcinoma; B/J, Boyd and Jewer classification of mandibular defects (L, lateral; C, central; H, hemimandible; LCL, lateral-central-lateral); CT, computed tomography; CTA, computed tomography angiography; FFF, fibular free flap; ICU, intensive care unit; PRC, packed red cells; SD, standard deviation; THB, Thai Baht; USD, United States dollar; BD, blended diet.

Table 2 presents the operative parameters and reconstructive details of the series. Squamous cell carcinoma accounted for 61% of cases, and lateral-type mandibular defects (L, LC, LCL) represented 78% of reconstructions. All procedures utilized osteocutaneous fibula free flaps with single-paddle soft-tissue components (mean 4 × 6 cm). Preoperative CT facial bone imaging was performed in all cases, and CTA of the leg was performed in 83%, with peroneal pedicle use in 100%. The mean defect length was 83.8 mm, the mean ischemia time was 101 ± 32 minutes, and the total operative time was 613 ± 110 minutes. All flaps survived (100%), no routine ICU admission was required, and the mean hospital stay was 15.6 days. These findings demonstrate the feasibility and reliability of low-cost, surgeon-driven 3D workflow in a regional center setting.

DISCUSSION

This study demonstrates the feasibility and reliability of an in-house, low-cost 3D printing workflow for mandibular reconstruction with fibula free flap (FFF) in a regional hospital setting. All 18 flaps survived with no routine postoperative ICU admission, and both ischemia and total operative times were comparable to those reported from tertiary centers using commercial computer-assisted design/manufacturing (CAD/CAM) systems. These findings confirm that affordable, surgeon-driven virtual planning can achieve high surgical precision and favorable outcomes while substantially reducing cost and logistical barriers.

The fibula free flap remains the gold standard for mandibular reconstruction because of its reliable vascularity, sufficient bone stock, and ability to undergo multiple osteotomies.^{1,3} However, conventional freehand reconstruction is technically demanding and time-consuming. Over the past two decades, computer-assisted surgery (CAS) and virtual surgical planning (VSP) have transformed maxillofacial reconstruction by improving geometric accuracy, flap fitting, and symmetry.⁴⁻⁶ Yet, widespread application of commercial CAD/CAM systems has been limited by high production costs and reliance on external engineering support.^{4,9}

Several groups have therefore explored in-house or open-source approaches that empower surgeons to perform 3D planning and model fabrication independently.¹⁰⁻¹³ Culié et al. (2016) demonstrated that the implementation of virtual planning and guided surgery (VPGS) significantly reduced fibular flap ischemia time from 171 to 98 minutes while maintaining comparable total operative time.⁸ Bosc et al. (2017) confirmed that internal manufacturing of cutting guides improved accuracy and eliminated outsourcing delays.⁷ Damecourt et al. (2020) reported a fully surgeon-performed planning method producing accurate models within 72 hours—compatible with urgent

oncologic surgery.⁹ Similarly, Ganry et al. (2017) achieved sub-millimeter precision (< 1 mm) using an open-source workflow based on OsiriX, MeshLab, and Blender,¹⁰ and Dowgierd et al. (2022) confirmed precise replication of pre-operative design in 3D-planned reconstructions.⁶

Our present results parallel those of these prior studies (Table 3). The mean ischemia time of 101 ± 32 minutes and total operative time of 613 ± 110 minutes fall within the same range reported for European tertiary centers using VSP workflows. Despite being implemented in a regional Thai hospital with limited resources, flap survival reached 100%, and no patient required routine ICU care. These outcomes validate that a locally fabricated, open-source-based workflow can deliver outcomes comparable to high-cost commercial systems.

Table 3 Comparative summary of selected representative studies on 3D-assisted mandibular reconstruction using fibula free flaps. The Lampang series shows ischemia and operative times comparable to high-cost virtual planning systems, while maintaining the lowest model cost ($< \$3$ USD) and a fully in-house workflow.

Several practical adaptations contributed to this success. All cases were planned using Blender, a freely available open-source modeling platform, and printed with a desktop fused-deposition (FDM) printer at a mean in-house 3D printing cost of 108.8 ± 16.0 THB per case (range, 80-150 THB; approximately USD 3.0). The entire process—from CT segmentation to sterilizable model production—was completed within 24 hours. This turnaround time is critical for oncologic patients requiring prompt resection and reconstruction. Operations were performed under high magnification using a Zeiss Tivato 700 microscope, with assistance from well-trained plastic scrub nurses, who ensured consistent microvascular results. The ability to iterate plate conformation and guide design independently allowed personalized planning without external delays.

3D planning and printing approach shortens preoperative lead time by eliminating coordination and production delays associated with outsourced commercial providers. This streamlined workflow enables earlier surgical scheduling, which is particularly advantageous for patients with head and neck malignancies, in whom delays to definitive surgery may increase

Table 3 Comparison of the in-house 3D printing workflow with previous reports

Study / Year	Country / Setting	Workflow Type	N	Mean Ischemia Time (min)	Total OR Time (min)	Model Production / Lead Time	Estimated Cost (USD)	Key Features / Outcomes
Panich et al. (2025)	Thailand (Regional Hospital)	In-house open source (Blender, PLA, FDM)	18	101 ± 32	613 ± 110	< 24 h (in-house)	3.0 /case (108.8 THB)	Surgeon-driven design; microscope-assisted (Zeiss Tivato 700); plastic-trained nurses; no ICU; flap survival 100%
Bosc et al. (2017) <i>Int J Oral Maxillofac Surg</i>	France (Tertiary cancer center)	In-house CAD/CAM	18	N/A	360-600 (mean 422)	< 48 h (3-15 d, mean 5.1 d)	~200-300	Internal manufacturing reduced ischemia time and improved accuracy
Ganry et al. (2017) <i>J Stomatol Oral Maxillofac Surg</i>	France	Open source (OsiriX + Blender)	3	N/A	N/A	72-96 h	N/A	Accuracy < 1 mm; deformation after sterilization < 0.2 mm; surgeon-operated workflow
Damecourt et al. (2020) <i>Eur Ann ORL HNS</i>	France (CHU Montpellier)	In-house 3D printing by surgical team	7	55	N/A	< 72 h	< 50	All planning, printing, and plate bending are done by surgeons; compatible with urgent cancer cases
Orabona et al. (2018) <i>Surg Oncol</i>	Italy (University Hospital)	Low-cost self-made CAD/CAM	4	N/A	N/A	~72 h	< 100	Demonstrated cost-effective guide fabrication without engineers
Culié et al. (2016) <i>Eur Ann ORL HNS</i>	France (Nice)	Virtual Planning & Guided Surgery (VPGS)	29	98 ± 45	481 ± 95	10-14 days (external vendor)	> 500	Significant ischemia time reduction vs conventional (171 → 98 min)
Dowgierd et al. (2022) <i>Oral Oncol</i>	Poland (National Cancer Center)	VSP + Individual Implants	21	N/A	N/A	2-3 weeks	> 1000	3D accuracy ± 7.7 mm; validated in pediatric/adult series; high precision but high cost

the risk of tumor progression.

From an economic standpoint, the mean total treatment cost of $\approx$ 244,000 THB was markedly lower than international averages for CAD/CAM-assisted reconstructions, where guide fabrication alone may exceed USD 300 per case.^{7,9,10} Our in-house workflow thus represents a practical model for resource-limited or regional centers, enabling equitable access to digital reconstructive technology.

However, successful implementation depends on the availability of personnel with expertise in three-dimensional planning and 3D printing, which may limit reproducibility and generalizability in centers lacking technical experience or institutional support.

Compared with commercially customized systems, the in-house 3D planning and cutting guide workflow may yield less precise bony apposition, as we occasionally observed small intersegmental gaps between the fibula and mandible. This likely reflects the use of standard, non-customized reconstruction plates. Nevertheless, meticulous intraoperative plate contouring mitigated this issue, and flap survival and early functional outcomes were not compromised.

Nonetheless, certain limitations remain. This was a single-center retrospective series with a limited sample size and heterogeneous indications. We did not objectively validate geometric accuracy using postoperative 3D superimposition. Long-term functional and aesthetic assessments, as well as patient-reported outcomes, remain areas for future study. However, the uniform success rate and reproducibility across 18 cases suggest this low-cost workflow has a short learning curve and is highly reliable once the surgical team is familiar with digital planning.

Future development could include integration of intraoperative navigation, photogrammetry, or augmented-reality guidance to further enhance precision. Regional collaboration networks could also standardize training and share open-source design libraries, thereby extending the benefits of this technology to other reconstructive domains such as midfacial or orbital defects.

CONCLUSION

This study confirms that in-house, low-cost 3D printing using open-source software is a feasible, accurate, and cost-effective solution for mandibular reconstruction with fibula free flap. The protocol enables surgeon-led virtual planning, rapid model production, and dependable clinical outcomes comparable to high-cost commercial CAD/CAM systems. By removing the dependence on outsourced manufacturing, this workflow strengthens reconstructive capability in regional hospitals and

promotes equitable access to advanced microsurgical reconstruction in resource-limited settings.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest related to this work.

AUTHOR CONTRIBUTIONS

- **Dr. Thanyanan Panich:** Conceived the study concept, collected and compiled patient data, coordinated multidisciplinary collaboration, and contributed to manuscript preparation.
- **Dr. Ueaungkun Sitthimongkon:** Designed the study framework, supervised data analysis and surgical methodology, and performed critical revision of the manuscript for important intellectual content.
- Both authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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