



Patient-Specific 3D-Printed Titanium Implant for Mandibular Reconstruction after Ameloblastoma Resection: A Review of the Digital Surgical Workflow

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Abstract

Ameloblastoma is benign, locally aggressive and unforgiving of incomplete excision, so its treatment produces segmental mandibular defects in patients who are otherwise well and who will live with the reconstruction for decades. That combination—a curable tumour, a long horizon and a demand for function rather than survival—is what has driven the digital workflow further in this disease than in oncological resection generally.

Objectives: To review the published evidence on virtual surgical planning, patient-specific implants and additively manufactured titanium in mandibular reconstruction after ameloblastoma resection, and to establish what the digital workflow demonstrably improves.

Material and Methods: A narrative review. MEDLINE, Embase and the Cochrane Library were searched from January 2010 to May 2026 for cohort studies, comparative series, systematic reviews with meta-analysis and accuracy studies addressing virtual planning, computer-aided design and patient-specific implants in mandibular reconstruction. Values were extracted from the primary reports and tabulated without pooling.

Results: Recurrence after conservative excision of ameloblastoma is reported between 55% and 90%, against 15% to 25% after segmental resection with margin, which establishes the defect that must then be reconstructed. Meta-analysis of virtual planning against freehand technique shows operative time reduced by 44.6 minutes and ischaemia time shortened, with reconstruction accuracy improved—intercondylar deviation of 2.0 mm against 3.9 mm and gonial angle deviation of 3.6 degrees against 7.7 degrees—but no difference in major or minor complications.

Conclusion: The digital workflow reliably improves geometric accuracy and operative efficiency. It has not been shown to reduce complications, and the evidence for patient-specific titanium implants specifically remains observational. Its strongest justification in ameloblastoma is that accurate restoration of occlusal geometry is what makes later dental rehabilitation possible in a young patient.

Abbreviations: VSP – Virtual Surgical Planning, CAD-CAM – Computer-Aided Design and Manufacturing, PSI – Patient-Specific Implant, FFF – Fibula Free Flap, CT – Computed Tomography, OR – Odds Ratio.

Keywords: Ameloblastoma; Mandibular Reconstruction; Virtual Surgical Planning; Patient-Specific Implant; Additive Manufacturing

Introduction

Ameloblastoma is a benign odontogenic tumour that behaves badly. It arises most often in the posterior mandible, grows slowly, expands rather than infiltrates, and almost never metastasises—yet it recurs relentlessly when excision is incomplete [1,2]. That behaviour dictates the surgery: conservative enucleation or curettage is followed by recurrence in 55% to 90% of solid and

multicystic lesions, against 15% to 25% after segmental resection with a bone margin of one to two centimetres (Figure 1) [3,4,5].

The consequence is a segmental mandibular defect in a patient who is otherwise healthy, often young, and who has been cured rather than palliated. Unlike reconstruction after squamous carcinoma, there is usually no adjuvant radiotherapy to compromise healing, and the horizon over which the

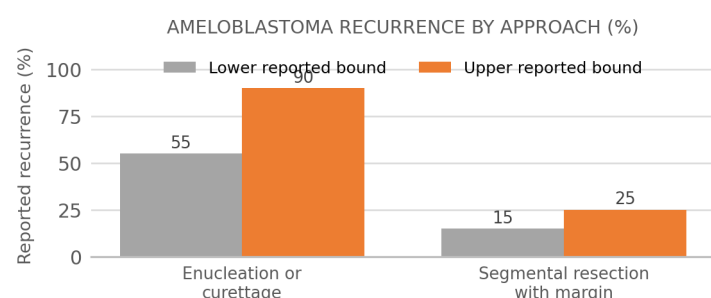


Figure 1: Reported recurrence of ameloblastoma after conservative excision and after segmental resection with margin, as a range across published series [3,4,5].

reconstruction must function is measured in decades. The reconstructive standard is expected to restore mandibular continuity, contour and occlusal relationship well enough to permit dental rehabilitation, not merely to close the defect [6,7].

The vascularised fibula free flap remains the reference technique for segmental defects, providing bone of adequate height and blood supply for osteotomy into multiple segments [8]. Its difficulty is geometric: recreating the curve of the mandible from a straight fibula requires closing wedge osteotomies whose angles and positions were, until recently, judged intraoperatively against a plate bent by hand. Accuracy therefore depended on the surgeon's estimation under ischaemic time pressure.

Donor choice is not entirely settled. The fibula supplies the greatest usable bone length and tolerates multiple osteotomies, which is why it dominates segmental reconstruction, but its vertical height is roughly half that of the native mandible. That mismatch matters because dental implants placed into a single fibular barrel sit low relative to the occlusal plane, and the resulting crown-to-implant ratio is unfavourable. Double-barrel configurations, vertical distraction and secondary grafting are the usual answers, each adding an operation. The iliac crest offers height at the cost of length and pedicle, and the scapula offers soft tissue at the cost of intraoperative positioning [6,8,22].

Virtual surgical planning displaces that judgement to the preoperative period. Resection and donor osteotomies are planned on segmented computed tomography data, transferred to theatre through printed cutting guides, and the osteosynthesis is provided by a patient-specific implant designed to the planned geometry and manufactured by selective laser melting rather than bent at the table [9,10]. This review examines what that workflow has been shown to improve, what it has not, and where the evidence for the titanium implant itself remains thin.

The inputs deserve as much attention as the output. Planning is only as good as the imaging it is built from: thin-slice computed tomography of the mandible and donor limb is the minimum, and where the tumour margin is uncertain on bone windows, fusion with magnetic resonance data has been used to define the resection more confidently than either modality alone [23]. Segmentation is

Approach	Reported recurrence	Comment
Enucleation or curettage	55–90%	Solid and multicystic disease [3,4]
Marginal resection	Intermediate	Depends on margin achieved [5,11]
Segmental resection, 1–2 cm margin	15–25%	Produces the reconstructive defect [4,5]
Conservative in unicystic disease	Lower	The main legitimate exception [1,11]

Table 1: Reported recurrence of ameloblastoma by surgical approach.

semi-automated but not automatic, and the boundary a clinician accepts on screen becomes the cut made in theatre. Errors introduced at this stage propagate through the entire workflow and are invisible by the time the guides arrive.

Material and Methods

Search strategy:

MEDLINE, Embase and the Cochrane Library were searched from January 2010 to May 2026. Terms combined controlled vocabulary and free text for ameloblastoma, mandibular reconstruction, virtual surgical planning, computer-aided design, patient-specific implant, additive manufacturing, selective laser melting and fibula free flap. Reference lists of systematic reviews and technique papers were hand-searched.

Eligibility and synthesis:

Comparative cohort studies, systematic reviews with meta-analysis, accuracy studies with defined geometric endpoints and case series reporting patient-level outcomes were eligible. Individual case reports were used only where they document a distinct technical approach. Values were extracted by one reviewer and checked by a second. The included studies differ in defect classification, donor site, planning software and accuracy metric, so results are presented descriptively and no pooling was attempted. No individual patient data were accessed and ethics approval was not required.

Results

The resection that sets the problem

Recurrence data establish why the defect exists at all (Table 1). Solid and multicystic ameloblastoma recurs in the large majority after enucleation, and meta-analysis of primary multicystic disease confirms the gap between conservative and radical approaches [3]. Unicystic disease behaves less aggressively and is sometimes managed conservatively, which is the main legitimate exception [1,11]. Recurrence has been documented within the reconstruction itself decades after apparently clear margins, which argues for long follow-up rather than for wider resection [12].

Outcome	Planned	Freehand	Difference
Operative time [14]	–	–	44.6 min
Ischaemia time [15]	73.8 min	109.9 min	36.1 min
Intercondylar deviation [16]	2.0 mm	3.9 mm	1.9 mm
Gonial angle deviation [16]	3.6	7.7	4.1
Major complications [14]	–	–	OR 1.03

Table 2: Comparative outcomes of virtual surgical planning against freehand technique in fibula-based mandibular reconstruction.

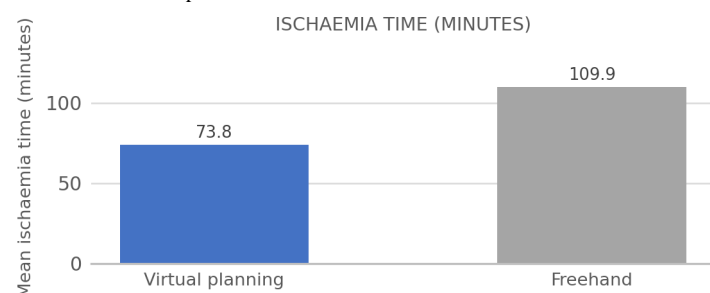


Figure 2: Ischaemia time in fibula-based mandibular reconstruction with virtual planning against freehand technique, from pooled series [15].

Histological subtype modifies that picture and is worth establishing before planning. The solid and multicystic forms behave as described; unicystic disease, particularly the luminal and intraluminal variants, is appreciably less aggressive, while a mural component brings it closer to the solid form in behaviour. Peripheral ameloblastoma of the soft tissues is a separate entity with a far better prognosis. Because the reconstructive commitment follows directly from the extent of resection, an incisional biopsy that establishes subtype before definitive surgery is not an academic exercise but the step that determines whether a segmental defect is created at all [1,2,4,11].

The margin requirement of one to two centimetres is therefore not a preference but the determinant of the reconstructive problem, and it is the reason planning must begin with the resection rather than with the flap. In the digital workflow the resection guide is designed first, against the planned margin, and the donor osteotomies are derived from the defect it creates—the reverse of the freehand sequence, in which the defect was discovered and then matched [9,13].

Immediate reconstruction is standard in this setting and is one of the advantages of a benign diagnosis. There is no waiting for definitive margin histology in the way that sometimes delays reconstruction in carcinoma, no adjuvant radiotherapy to compromise healing, and no oncological reason to defer. The practical constraint is instead the lead time for planning and manufacture, which fixes the operating date rather than the other way round, and which requires the resection to be planned before the patient is booked [24,25].

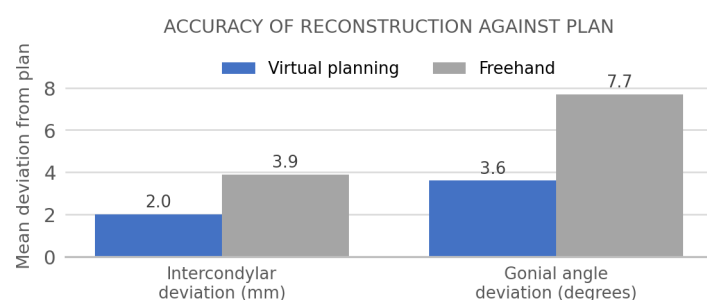


Figure 3: Accuracy of reconstruction against plan: mean intercondylar distance deviation and gonial angle deviation, planned against freehand [16].

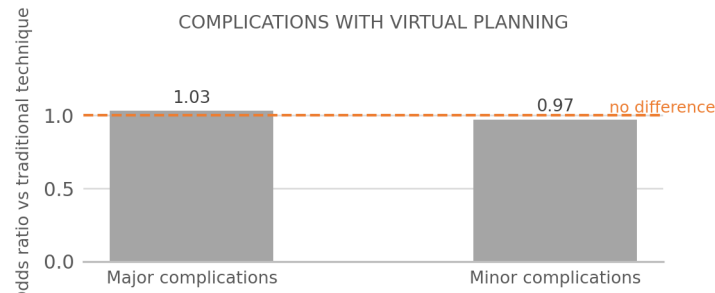


Figure 4: Odds ratios for major and minor complications with virtual planning against traditional technique; values near 1.0 indicate no difference [14].

What virtual planning demonstrably improves

Efficiency and accuracy are the two domains with comparative evidence (Table 2). Meta-analysis of virtual planning against traditional technique in fibula-based reconstruction found operative time reduced by 44.6 minutes, with a non-significant trend towards shorter admission [14]. Ischaemia time falls similarly, reported at 73.8 minutes with planning against 109.9 minutes freehand across pooled series (Figure 2), which matters because prolonged ischaemia is associated with flap compromise [15].

Accuracy is the more convincing gain (Figure 3). A meta-analysis of relatively homogeneous cases found mean intercondylar deviation of 2.0 mm with planning against 3.9 mm freehand, and gonial angle deviation of 3.6 degrees against 7.7 degrees [16]. Those differences are small in absolute terms and consequential in practice, because condylar position determines whether the reconstructed mandible articulates correctly and gonial angle determines facial contour.

What the comparative evidence does not show is a reduction in complications. The same meta-analysis found no difference in major complications (odds ratio 1.03) or minor complications (odds ratio 0.97), and independent systematic reviews reach the same conclusion (Figure 4) [14,17,18]. Some single-centre series report lower nonunion rates with planned reconstruction, but these are observational and susceptible to the improvement that any centre shows over time [19]. The honest summary is that the workflow makes the operation faster and the result geometrically closer to plan, without yet demonstrating that patients suffer fewer adverse events.

It is worth being clear why an accuracy gain might not translate into fewer complications. The events that dominate complication counts in this surgery —flap failure, wound dehiscence, infection, plate exposure —are driven by vascular anastomosis, soft tissue cover, comorbidity and, in cancer patients, radiotherapy. None of those is much affected by whether the osteotomy angles matched a plan to within two degrees. A workflow that improves geometry should be expected to improve geometric outcomes, and the absence of a complication signal is a reasonable result rather than a disappointing one [14,17,18].

The patient-specific implant

The titanium implant is a distinct question from the planning. Conventional reconstruction plates are bent intraoperatively, which work-hardens the metal at the bends and introduces stress concentrations; plate fracture and screw loosening are recognised late failures. An implant designed to the planned geometry and produced by selective laser melting requires no bending, and the theoretical argument is that its mechanical behaviour should therefore be more predictable [10,20].

The clinical evidence for that proposition is thinner than the enthusiasm suggests. Series using patient-specific plates report acceptable union and low fracture rates, but they are small, uncontrolled and heterogeneous in defect type, and no randomised comparison against conventional plating exists [21,22]. Plate exposure remains the commonest local complication in reported series and appears related to soft tissue cover and to segment positioning rather than to how the plate was manufactured [23].

Biomechanical work supports the mechanical argument even where clinical data do not. Laboratory comparison of computer-designed plates against conventional plates bent to the same geometry shows differences in stiffness and fatigue behaviour attributable to the absence of work-hardening at the bends [31]. That is a real finding about metal, and it is reasonable to expect it to translate into fewer late fractures. It is not, however, the same as having observed fewer late fractures in patients, and the distinction is worth keeping visible when the technology is discussed with a patient.

Accuracy also degrades between plan and outcome in ways the workflow does not eliminate. Studies measuring postoperative position against the virtual plan report segment deviations of several millimetres, greater posteriorly than anteriorly, and condylar displacement that can be substantial where cutting guides seat imperfectly against soft tissue [23]. The plan is a specification, not a guarantee, and the discrepancy is largest exactly where the anatomy is least accessible.

The failure modes are also worth naming, because they recur across series. Guides can seat on soft tissue rather than bone and shift by millimetres; the mandible can be positioned differently at

operation from the position captured on the planning scan, particularly at the condyle; and where the tumour has expanded the cortex, the surface the guide was designed against may no longer be the surface presented at surgery. Each is a transfer error rather than a planning error, which is why intraoperative verification of guide position, and a willingness to abandon the guide when it does not seat convincingly, remain part of the technique [13,29,30].

Cost, time and where the workflow is delivered

Commercial planning and manufacture add cost and lead time, typically one to three weeks between imaging and delivery of guides and implant, which is acceptable in a benign tumour and problematic in malignant disease. In-house planning using open-source segmentation and desktop printing has been described as a means of reducing both, with outcomes comparable to commercial workflows in reported series, though it transfers regulatory and quality responsibility to the unit [24,25]. Cost-effectiveness has been argued from reduced operative time, but the analyses are sensitive to assumptions about theatre cost and have not been confirmed prospectively [26,27].

The regulatory position on in-house manufacture is the part most often glossed over. A guide or implant produced commercially arrives as a regulated medical device with a conformity assessment behind it; the same object printed in a hospital laboratory does not, and the responsibility for material traceability, sterilisation validation and dimensional verification transfers to the unit that made it. Several groups have described in-house pathways in detail and report good outcomes, but the published descriptions are of centres that built a quality system alongside the printer rather than in place of one [24,25].

Discussion

The evidence supports a narrower claim than the literature's enthusiasm implies. Virtual planning shortens the operation and improves how closely the reconstruction matches the intended geometry. It has not been shown to reduce complications, and the patient-specific implant —the most visible and most expensive component —has the weakest comparative evidence of any element in the workflow.

That said, geometric accuracy is not a cosmetic endpoint in this disease. The patient is typically young, cured, and expecting to eat and speak normally for decades, and the realistic goal is osseointegrated dental rehabilitation. That requires the neomandible to sit in a position that allows implants to be placed in a prosthetically useful relationship to the opposing arch, which is a geometric problem the freehand technique solves inconsistently [6,7,28]. Where planning is justified, it is justified on that basis rather than on complication rates.

Two practical points follow. Planning should begin from the oncological resection and the intended dental outcome

Component	Function	Evidence
Segmentation and planning	Defines resection to oncological margin	Improves accuracy [14,16]
Resection cutting guide	Transfers the planned margin to theatre	Main source of residual error [23]
Donor osteotomy guide	Sets segment angles before ischaemia	Shortens ischaemia time [15]
Patient-specific implant	Fixation without intraoperative bending	Observational only [21,22]
Prosthetic pre-planning	Positions bone for later implants	Determines functional outcome [6,7]

Table 3: Components of the digital workflow and what each contributes.

simultaneously (Table 3), since a reconstruction that is anatomically elegant but prosthetically unusable has failed at the thing that matters most to the patient. And the workflow's dependence on guide seating deserves more attention than it receives: the measured deviations arise largely at that step, and it is the one part of the chain still performed by hand under time pressure [23,29].

What the field lacks is a randomised comparison with function as the endpoint. Existing studies measure millimetres and minutes because those are easy to measure; what patients experience is whether they can chew, whether the reconstruction still works in fifteen years, and whether implants could be placed. Registry follow-up of the kind that exists in arthroplasty would answer more than another accuracy study [30,31].

Long-term follow-up is the other gap, and it bears particularly on this patient group. A reconstruction in a thirty-year-old cured of a benign tumour has to survive four or five decades of loading, during which the plate may need removal, implants may fail and the opposing dentition will change. Almost nothing in the cited literature follows patients beyond a few years, so statements about the durability of patient-specific fixation are extrapolations from short series [21,30]. That is an argument for structured follow-up rather than against the technique.

Function should also be measured in terms patients recognise. Diet, speech intelligibility, oral competence and appearance are what determine whether a reconstruction is judged successful, and validated instruments exist for all of them, yet most of the digital planning literature reports millimetres and minutes instead. Where dental rehabilitation has been studied directly, implant survival in vascularised bone is good and the limiting factor is position rather than osseointegration—which is precisely the variable planning is supposed to control, and precisely the endpoint that would make the case [7,28].

Study limitations

This is a narrative rather than a systematic review: studies were selected against stated criteria but without duplicate screening of the full yield, and no risk-of-bias instrument was applied. The

comparative literature is dominated by fibula-based reconstruction for mixed indications, so figures are transferred to ameloblastoma by inference. Accuracy metrics are not standardised between studies. Evidence specific to additively manufactured titanium is observational and drawn from small series. The review does not cover scapular or iliac donor sites in detail, paediatric reconstruction, or the management of recurrent disease within a previous reconstruction.

Conclusion

After segmental resection of ameloblastoma, virtual surgical planning with printed guides and a patient-specific titanium implant produces a reconstruction closer to the intended geometry and a shorter operation than freehand technique. It has not been shown to reduce complications, and the implant itself rests on observational evidence. Its justification in this disease is specific: the patient is young and cured, the reconstruction must serve for decades, and accurate restoration of occlusal geometry is what makes dental rehabilitation achievable. Accuracy should be understood as a means to that end rather than as an outcome in itself.

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