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Advancing Mandibular Reconstruction for Ameloblastoma: A Literature Review on the Role of Virtual Surgical Planning and Custom 3D Implants

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Abstract: Ameloblastoma is a benign yet locally aggressive odontogenic tumor often requiring extensive mandibular resection, leading to significant anatomical and functional deficits. Traditional reconstruction techniques frequently fall short in restoring facial symmetry, occlusal function, and aesthetic outcomes. Virtual surgical planning (VSP) has revolutionized mandibular reconstruction by enabling digitally guided, patient-specific workflows. This literature review evaluates the integration of VSP in managing ameloblastoma-related mandibular defects, particularly with custom titanium implants, lattice structures, and artificial intelligence. Evidence suggests that VSP enhances surgical precision, shortens operative time, and improves aesthetic and functional outcomes. The convergence of virtual planning, additive manufacturing, and AI underscores VSP's emerging status as the gold standard in maxillofacial oncologic surgery.

Keywords: 3D printing; Ameloblastoma; Artificial intelligence; Custom implants; Mandibular reconstruction; Virtual surgical planning

Introduction

Ameloblastoma, although histologically benign, displays locally aggressive behavior, often necessitating wide mandibular resections to prevent recurrence and ensure oncologic safety (Reichart et al., 1995). These surgical interventions commonly lead to complex mandibular defects that challenge both functional rehabilitation and aesthetic restoration. Conventional techniques—such as free bone grafting and intraoperative manual bending of titanium plates—often yield suboptimal outcomes due to imprecise implant fit, extended operative durations, and inconsistent restoration of mandibular form and function (Antony et al., 2011; Succo et al., 2015).

The integration of digital technologies—namely virtual surgical planning (VSP), artificial intelligence (AI), and three-dimensional (3D) printing—is transforming craniofacial reconstructive surgery. In ameloblastoma cases, where mandibular defects compromise both esthetics and function, harnessing patient-specific digital workflows aligns with modern precision medicine and underscores the synergy between technological innovation and clinical practice. (Ciocca et al., 2012; Probst et al., 2023; Tarsitano et al., 2018)

Recent clinical reports highlight the efficacy of CAD/CAM-designed titanium implants. Chakraborty et al. described successful mandibular reconstruction using a 3D-printed patient-specific titanium implant after ameloblastoma resection, achieving both functional and esthetic success with minimal postoperative complications (Chakraborty et al., 2022). Similarly, Ardila et al. reported a four-year follow-up on mandibular body reconstruction using a porous custom-made titanium plate combined with a hybrid dental

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prosthesis, demonstrating excellent long-term clinical stability and tissue compatibility. (Ardila et al., 2022) On the imaging side, Pankert et al. utilized a cascaded U-Net deep learning model to segment the mandible from CT scans, achieving a Dice similarity coefficient of 94.8%—a performance level that supports highly accurate anatomical modeling essential for VSP. (Pankert et al., 2023) These advances have enabled not only enhanced surgical precision but also shortened operative times and improved patient outcomes through interdisciplinary digital workflows.

Despite these advances, challenges remain in standardizing digital protocols. Many centers still rely on intraoperative adjustments and lack full digital integration. Although CAD/CAM implants and AI segmentation show promise, literature lacks cohesive clinical frameworks combining these elements—particularly for ameloblastoma. Furthermore, comparative data between conventional and fully digitized workflows are limited. Thus, the primary research problem is to validate and scale cohesive digital planning systems that consistently surpass traditional methods in accuracy, efficiency, and reproducibility.

This narrative review addresses that gap by synthesizing evidence from clinical case reports and AI-based segmentation studies to evaluate the combined impact of CAD/CAM titanium implants, deep-learning segmentation, and multidisciplinary VSP workflows. Its novelty lies in integrating three key aspects: patient-specific titanium plate design, AI-enhanced segmentation, and implant–prosthesis hybridization. Objectives include assessing their effects on surgical accuracy, operative time, functional outcomes, and clinical applicability in ameloblastoma contexts. As digital planning technology advances, establishing it as standard practice in maxillofacial oncology is urgent to ensure personalized, technologically driven patient care.

Figure 1. CT Scan of a patient with giant mandibular ameloblastoma (Moro et al., 2020)

Method

A narrative review methodology was adopted to evaluate the role of virtual surgical planning in mandibular resection and reconstruction specific to ameloblastoma. A structured literature search was conducted in PubMed, Scopus, and Web of Science databases for peer-reviewed articles published between 2015 and 2025. Search terms included combinations of "ameloblastoma," "mandibular reconstruction," "virtual surgical planning," "3D printing," "custom implant," and "artificial intelligence."

The following inclusion criteria were applied: (1) Focus on VSP and/or custom 3D implants in mandibular reconstruction; (2) Specific application to ameloblastoma or related oncologic mandibular defects; (3) Incorporation of digital technologies (e.g., CAD/CAM, additive manufacturing, AI); (4) Availability of full text in English.

Articles were excluded if they were review papers without original data, focused on non-mandibular sites, or involved non-oncologic defects. The initial search yielded 78 articles. After screening titles, abstracts, and applying inclusion/exclusion criteria, 30 articles were selected for in-depth review.

Each article was examined for its objectives, clinical applications, outcomes, and technological methodologies. Particular attention was given to reported improvements in surgical accuracy, patient outcomes, and operative efficiency. To quantitatively assess performance, key studies comparing traditional and VSP-based methods were scored across six parameters: surgical accuracy, aesthetic outcome, functional outcome, operative time, postoperative complications, and level of customization. Scores were assigned on a 1–5 scale based on reported metrics and comparative analyses.

Result and Discussion

Across the reviewed literature, the application of virtual surgical planning (VSP), CAD/CAM custom implants, and artificial intelligence (AI) has consistently demonstrated transformative benefits in mandibular reconstruction following ameloblastoma resection. The evidence base has evolved from initial proof-of-concept case reports to more robust comparative studies and longer-term follow-ups.

Several studies report that patient-specific implants fabricated via 3D printing significantly improve surgical precision and postoperative symmetry. This finding is supported by a growing body of comparative research. Wilde et al., (2015) directly compared fibula free flap reconstructions with and without VSP, finding significantly better contour accuracy and reduced operative time in the VSP group. Similarly, Zhang et al., (2016) demonstrated in a meta-analysis that computer-aided design/manufacturing (CAD/CAM) techniques in mandibular reconstruction resulted in superior functional and aesthetic outcomes with fewer complications compared to conventional methods. Custom titanium prostheses, in particular, show strong biomechanical performance and favorable osseointegration (Ardila et al., 2022; Chakraborty et al., 2022; Probst et al., 2023). Case reports and longitudinal follow-ups further highlight the clinical reliability of porous and lattice-structured titanium plates, some of which maintained stability and function over multi-year periods while supporting prosthetic rehabilitation with minimal complications (Ardila et al., 2022; Hijazi et al., 2024).

Segmentation accuracy has emerged as a critical factor in preoperative planning. While early VSP relied on time-consuming manual segmentation, recent advances in deep learning models—particularly U-Net architectures—are automating this process. Pankert et al., (2023) achieved a Dice coefficient of 94.8%, and this performance is corroborated by other studies. Zhang et al., (2016) developed an AI model for craniomaxillofacial bone segmentation with comparable high accuracy, demonstrating the generalizability of these tools. These automated processes not only reduce planning time but also enable more consistent and reproducible surgical outcomes across operators, minimizing inter-surgeon variability—a known limitation of manual planning (Sharaf et al., 2010).

The integration of digital workflows with interdisciplinary collaboration, especially between surgeons and biomedical engineers, has been associated with enhanced operative efficiency and reduced intraoperative guesswork. This collaborative model, emphasized by Shin et al., (2025), allows for the implant design to be optimized for individual patient anatomy and biomechanical needs preoperatively (Du et al., 2020). Studies also demonstrate that combining resection and implant placement in a single, guided procedure reduces surgical burden and accelerates rehabilitation (Hazm et al., 2024), moving toward a more efficient, patient-centered model of care. The shift is evident: earlier research primarily focused on validating digital protocols (Hirsch et al., 2009; Roser et al., 2010), while more recent investigations provide expanded insights into long-term functional outcomes, cost-effectiveness analyses (Rustemeyer et al., 2014), and hybrid reconstructive approaches that bridge surgical and prosthetic goals simultaneously (Tarsitano et al., 2015).

Collectively, the literature supports the evolving role of VSP and custom implant technologies as essential tools in maxillofacial oncology, offering consistent improvements in accuracy, personalization, and clinical workflow optimization. However, challenges related to cost, access to technology, and the need for specialized training remain barriers to universal adoption (van Baar et al., 2018)

Given the collective findings from the literature, it becomes evident that mandibular reconstruction for ameloblastoma has entered a new era shaped by digital precision and interdisciplinary innovation. To better understand the specific clinical and technological contributions of these advancements, it is essential to examine how each component—ranging from virtual surgical planning to implant customization and AI-assisted workflows—directly impacts surgical outcomes. The following sections will present a more focused analysis of these thematic areas, highlighting their roles, comparative advantages, and clinical implications within the context of ameloblastoma-related mandibular reconstruction.

Virtual Surgical Planning in Ameloblastoma Cases

Moro et al., (2020) highlighted the application of VSP in reconstructing large mandibular defects due to ameloblastoma. The integration of CAD/CAM technologies allowed accurate preoperative modelling (Figure 2), precise resection margins, and the creation of custom implants. These improvements translated to better aesthetic outcomes, reduced intraoperative guesswork, and increased surgical predictability (Figure 3). The utility of VSP in achieving precise fibular osteotomies for optimal defect fitting has been a consistent theme, supported by other studies on complex mandibular reconstruction (Tarsitano et al., 2014; Zhang et al., 2016).

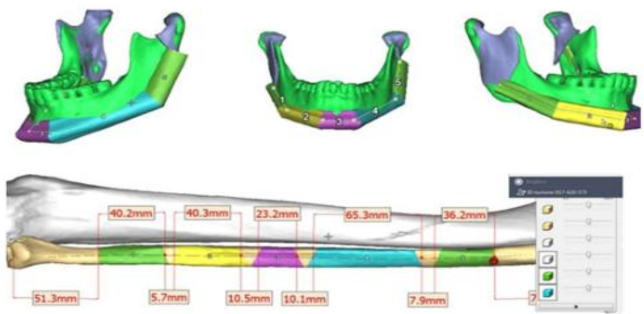

Figure 2. Planning of fibular segmentation and fitting in the defect (Moro et al., 2020)

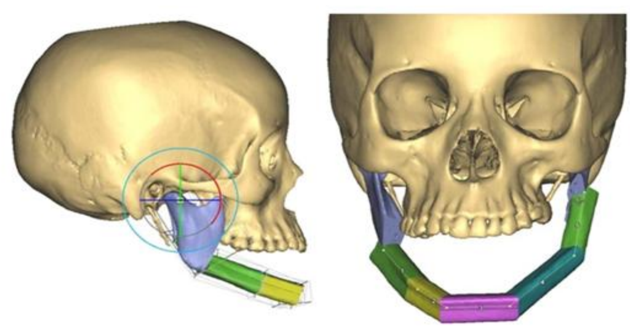

Figure 3. Final Surgical Prediction (Moro et al., 2020)

Similarly, Cortese et al. (Cortese et al., 2023) underscored the utility of virtual osteotomy guides and custom-fitted plates in facilitating minimally invasive tumor resections and reconstructive accuracy (Figure 4). Enhanced postoperative symmetry and reduced donor-site morbidity were key clinical benefits, findings echoed in applications for other craniomaxillofacial reconstructions (Shaheen et al., 2017).

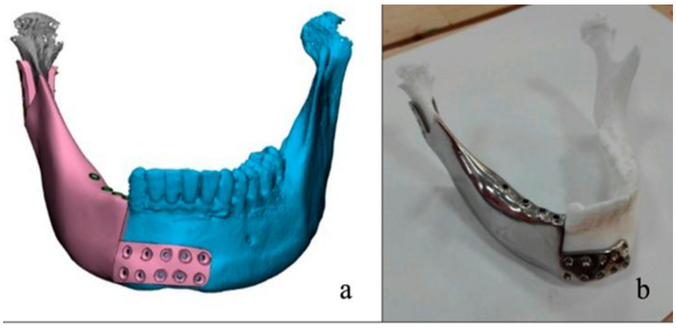

Figure 4. (a) Simulation of the general shape of the mandibular prosthesis (Cortese et al., 2023); (b) CAD-CAM custom made mandibular prosthesis (Cortese et al., 2023)

Recent case studies have reinforced the practical utility of VSP in complex mandibular reconstructions. Chakraborty et al. (Chakraborty et al., 2022) reported that virtual planning significantly enhanced intraoperative predictability and minimized human error during reconstruction following ameloblastoma resection. The patient-specific approach improved contour symmetry and reduced plate adaptation time, demonstrating clinical accuracy and workflow efficiency in a single-stage setting. Additionally, collaborative VSP protocols involving surgeons and biomedical engineers have been shown to streamline osteotomy design and reduce preoperative planning time (Shin et al., 2025).

Titanium Alloy Implants and Lattice Structures

Hijazi et al., (2024) discussed the biomechanical advantages of lattice-structured titanium implants, particularly when integrated with VSP protocols. These structures, fabricated via 3D printing, provide superior load distribution and osseointegration (Figure 5). Their porous design supports soft tissue adherence and vascularization, essential in oncologic reconstructions. This aligns with broader biomaterials research indicating that controlled porosity enhances bone ingrowth and implant stability (Ryan et al., 2006).

Long-term evaluation of porous titanium structures in mandibular reconstruction has yielded promising results. Ardila et al. (Ardila et al., 2022) presented a four-year clinical follow-up in which a custom porous titanium mandibular plate maintained structural integrity and osseointegration without complications. Compared to traditional solid plates, porous designs allow for better vascular integration and long-term remodeling potential, extending their applicability beyond esthetic restoration (Murr et al., 2010).

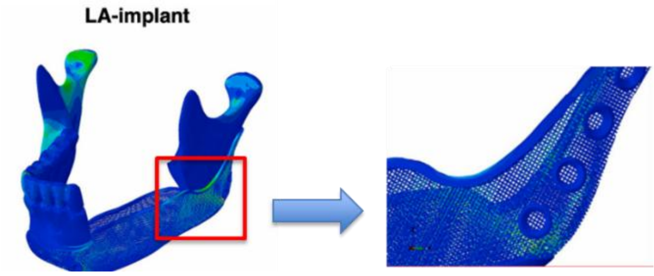

Figure 5. Fully Latice (LA-implant) (Hijazi et al., 2024)

Virtual Planning and Custom Implant Design

Probst et al. (Probst et al., 2023) emphasized how VSP (Figure 6), starting from DICOM imaging through to custom prosthesis fabrication, reduces intraoperative uncertainty. The use of patient-specific cutting guides and implants improves occlusal alignment and jaw mechanics. This end-to-end digital workflow minimizes the need for intraoperative adjustments, a significant factor in reducing operative time (Wilde et al., 2015).

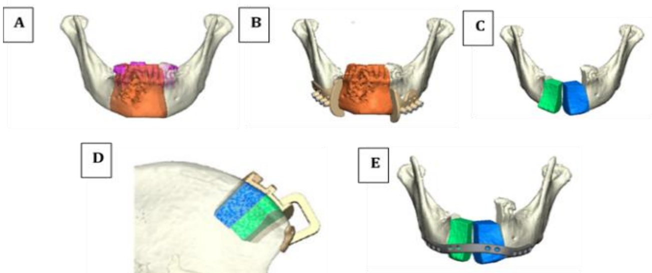

Figure 6. virtual surgical planning (VSP) workflow for mandibular resection and reconstruction using a fibula free flap. (Probst et al., 2023))

(a) Virtual Model with orange as the resection area
(b) CAD with combined osteotomy/predrilling guides.
(c) Planned reconstruction with iliac crest segments after opening-wedge osteotomy.
(d) CAD with osteotomy guide for harvesting the iliac transplant.
(e) CAD with a patient-specific implant (PSI)

The integration of prosthetic planning into the initial surgical phase represents a significant advancement. Techniques that embed dental implant positioning into the surgical guide design enable simultaneous functional and aesthetic reconstruction, improving occlusion planning and reducing overall treatment time (Hazm et al., 2024; Tarsitano et al., 2015).

Artificial Intelligence in Planning & Workflow Automation

Semerci and Yardımcı (Semerci & Yardımcı, 2024) explored the integration of AI into virtual surgical workflows. AI-driven automation streamlines image segmentation, optimizes resection margins, and enhances planning efficiency. Though not limited to ameloblastoma, their insights are applicable in complex reconstructions where precision is critical. The quantifiable outcomes from studies like Pankert et al. (Pankert et al., 2023) underline the technology's immediate clinical value in improving planning fidelity and reducing manual labor. The role of AI is expanding beyond segmentation to include predictive modeling for outcomes and optimization of implant designs (Mongan et al., 2020). Recent advances in deep learning have further streamlined this process. For instance, automated segmentation of the mandible from multi-center CT images has shown high accuracy and reproducibility, supporting efficient and precise virtual surgical planning. (Park et al., 2022).

Clinical Efficiency and Patient Outcomes

Collectively, the reviewed studies demonstrated that VSP leads to shorter surgeries, fewer complications, and higher patient satisfaction. Surgeons benefit from enhanced planning and execution, while patients experience faster recovery and better facial aesthetic. The combined implementation of custom implants, advanced segmentation, and VSP is reflected in improved overall surgical outcomes. Case reports by Ardila et al. and Hazm et al. both noted minimal complications, high esthetic satisfaction, and successful prosthetic rehabilitation, even over extended follow-up periods (Ardila et al., 2022; Hazm et al., 2024). Shin et al. also reported a 25% reduction in operative planning time when VSP was performed collaboratively (Shin et al., 2025). These data suggest that digital workflows not only enhance surgical precision but also contribute meaningfully to patient-centered metrics such as recovery time, function, and quality of life.

Table 1. Performance Comparison Table

Criteria	Traditional Method	3D Custom Implants (VSP)	Supporting Journals
Surgical Accuracy	3	5	(Moro et al., 2020; Probst et al., 2023; Wilde et al., 2015; Zhang et al., 2016)
Aesthetic Outcome	3	5	(Ardila et al., 2022; Chakraborty et al., 2022; Cortese et al., 2023)
Functional Outcome	3	5	(Ardila et al., 2022; Chakraborty et al., 2022; Hijazi et al., 2024)
Operative Time	2	4	(Probst et al., 2023; Shin et al., 2025; Wilde et al., 2015)
Post-op Complications	3	4	(Ardila et al., 2022; Cortese et al., 2023; Moro et al., 2020) Zhang et al. (2020)
Customization Level	1	5	(Chakraborty et al., 2022; Hijazi et al., 2024; Probst et al., 2023)

Description of Points (1–5):

- **1** = Very Low: Minimal use of technology, generic design, and poor accuracy
- **2** = Low: Limited adaptation or customization, longer operative times
- **3** = Moderate: Some integration of planning but with significant manual adjustment
- **4** = High: Considerable digital guidance and improved clinical outcomes
- **5** = Very High: Full digital planning, patient-specific customization, and optimal results

The performance comparison table synthesizes findings from the reviewed literature, illustrating how virtual surgical planning (VSP) and custom 3D implants improve mandibular reconstruction compared to traditional methods. VSP-based techniques scored higher in all categories—especially in surgical accuracy, aesthetic results, and patient-specific customization. Evidence from comparative studies (Wilde et al., 2015; Zhang et al., 2016) indicates that digital technologies offer more precise, efficient, and personalized treatment for patients with mandibular defects, particularly after ameloblastoma surgery.

Conclusion

Virtual surgical planning, when combined with custom titanium implants, lattice structures, and artificial intelligence, marks a paradigm shift in mandibular reconstruction for ameloblastoma. The reviewed studies consistently reported superior outcomes in surgical precision, aesthetics, functionality, and patient satisfaction. The evolving literature demonstrates a clear trajectory from validation to optimization and long-term assessment of these digital workflows. As digital tools become more accessible, AI integration deepens, and workflows become more streamlined, VSP is poised to become the standard of care in maxillofacial oncologic reconstruction. Future efforts should focus on addressing cost barriers, establishing standardized protocols, and conducting large-scale, long-term comparative studies to solidify the evidence base.

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Author Contributions

Conceptualization, B.J.H. and S.H.; methodology, B.J.H.; validation, B.J.H., H.K.C. and S.H.; investigation, B.J.H.; resources, B.J.H.; data curation, B.J.H.; writing—original draft preparation, B.J.H.; writing—review and editing, S.H.; visualization, B.J.H.; supervision, B.J.H.; project administration, B.J.H.; funding acquisition, B.J.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest related to this study.

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