PATIENT-SPECIFIC IMPLANTS FOR MANDIBULAR RECONSTRUCTION AFTER TUMOR RESECTION

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Background. Mandibular reconstruction following tumor resection is a complex challenge in oral and maxillofacial surgery. While vascularized free bone flaps remain the gold standard, 3D-printed patient-specific implants (PSIs) have emerged as a highly predictable alternative, especially when free flap harvesting is contraindicated or avoided to minimize donor-site morbidity in young patients with benign entities like ameloblastoma. However, the long-term biomechanical impact of these highly rigid alloplastic structures on the temporomandibular joint (TMJ) complex requires deeper investigation.

Objectives. This literature review aims to evaluate the clinical and surgical efficacy of custom-made alloplastic implants in post-tumor mandibular reconstruction and analyze their long-term biomechanical limitations and pathological impact on condylar unit kinematics and TMJ remodeling.

Materials and Methods. A comprehensive literature search was conducted across PubMed, Scopus, and Web of Science databases for peer-reviewed clinical studies, cohort trials, and case reports published within the last decade. The focus was restricted to 3D-printed alloplastic PSIs (titanium, PEEK) utilized after mandibular tumor ablation. Data tracking virtual surgical planning (VSP) accuracy, functional outcomes, dental occlusion stability, and TMJ remodeling or condylar displacement were extracted and subjected to a *qualitative narrative synthesis.*

Results. The integration of VSP and additive manufacturing (SLM titanium) reduces total operative times by 15% to 35% and provides bone segment positioning accuracy within less than 1.5 mm. Primary occlusal stability is achieved in 92% to 95% of cases. However, long-term tracking (12–24 months) reveals distinct complications driven by the stress shielding phenomenon. Highly rigid monolithic plates transfer unmitigated masticatory loads directly to the cranial base, resulting in a 20% to 35% incidence rate of TMJ dysfunction, asymmetric joint space narrowing, and progressive flattening or translation of the condylar head within the glenoid fossa.

Conclusion. While PSIs offer exceptional immediate anatomical accuracy and eliminate donor-site morbidity, their extreme structural rigidity poses a long-term risk to joint kinematics in active individuals. Future protocols must incorporate patient-specific Finite Element Analysis (FEA) during the CAD design phase and mandate early postoperative gnathological rehabilitation, including custom occlusal splints, to preserve long-term joint function and quality of life.

Introduction

Mandibular segment defects resulting from the radical resection of benign or malignant tumors present a formidable and multi-disciplinary challenge in contemporary craniomaxillofacial and plastic-reconstructive surgery [1, 2]. The mandible plays a critical biomechanical role, actively contributing to mastication, deglutition, and speech production while establishing the essential structural framework of the lower third of the face [2]. Disruption of mandibular continuity post-segmental resection inevitably initiates a cascade of severe functional impairments, profound facial asymmetry, and subsequent psychological and social maladaptation for the patient[2, 3].

For several decades, microvascular autologous bone transplantation—primarily using the vascularized free fibula flap—has been considered the undisputed gold standard for restoring mandibular continuity [4]. However, this surgical approach is inherently associated with significant donor-site morbidity, prolonged operative times under general anesthesia, and extensive surgical trauma [5]. Furthermore, complex microvascular stages are frequently contraindicated or unfeasible in medically compromised patients, elderly cohorts, individuals with peripheral vascular disease, or cases where extensive bone harvesting is unnecessary due to the localized, non-infiltrative nature of certain benign tumors[5, 6].

The clinical integration of Virtual Surgical Planning (VSP) and additive manufacturing techniques has ushered in a transformative era in reconstructive oncology through the use of Patient-Specific Implants (PSIs)[7], custom-designed using high-resolution computed tomography (CT) data. Manufactured from biocompatible materials such as titanium alloys, polyetheretherketone (PEEK), or bioceramics, these custom biomaterials precisely mirror the native macro-anatomical contour of the resected bone segment [7, 8]. This method yields excellent cosmetic symmetry and drastically shortens intraoperative time by eliminating the traditional, free-hand manual bending of standard reconstruction plates at the operating table[9].

Nevertheless, the rapid expansion of clinical indications for these highly rigid, alloplastic monolithic structures has revealed distinct biological and technical limitations[6]. Possessing a modulus of elasticity that far exceeds native cortical bone, metallic custom plates induce the phenomenon of "stress shielding," fundamentally altering physiological strain and mechanical loading paths within the maxillofacial complex[10]. While the primary clinical mandate of a PSI in an elderly or heavily pre-treated oncological cohort is to serve as an immediate mechanical "salvage" procedure to minimize anesthesia time, its application in younger patients presenting with aggressive benign entities, such as ameloblastoma, demands strict long-term biomechanical forecasting[6]. Disruption of the dynamic musculoskeletal balance and rigid fixation without a vascularized bone component can lead to micro-instability at the screw-bone interface, stress-induced bone resorption, and progressive temporomandibular joint (TMJ) dysfunction[10, 11].

The purpose of this study is to perform a comprehensive analysis of the efficacy and biomechanical limitations of patient-specific implants (PSIs) in post-tumor mandibular reconstruction. Furthermore, this paper aims to present a clinical case report of a primary alloplastic PSI reconstruction in a 22-year-old female patient with a mural-type unicystic ameloblastoma, which demonstrated notable alterations in the positioning and long-term kinematic movement of the condylar unit within the glenoid fossa at the one-year postoperative follow-up.

Materials and Methods

A literature search was conducted across **PubMed, Scopus, and Web of Science** using the query: ("patient-specific implant" OR "CAD/CAM") AND "mandibular reconstruction" AND ("tumor" OR "ameloblastoma") AND ("temporomandibular joint" OR "biomechanics"). The search captured peer-reviewed clinical trials, cohort studies, and case reports from the last decade focused on 3D-printed alloplastic PSIs (titanium, PEEK).

Inclusion Criteria: Mandibular tumor resection defects; CAD/CAM or VSP workflows; long-term functional data on dental occlusion, TMJ kinematics, or FEA condylar displacement tracking.

Exclusion Criteria: Standard manually bent plates; trauma/infection defects; animal models; conference abstracts.

Extracted data parameters included tumor type, PSI material, follow-up timelines, and joint remodeling complications. A qualitative narrative synthesis was performed to analyze the clinical efficacy of PSIs and their biomechanical impact on condylar unit translation within the glenoid fossa.

Results

A qualitative and quantitative analysis of contemporary literature allowed for the systematization of clinical outcomes regarding the use of patient-specific implants (PSIs) in post-tumor mandibular reconstruction into three core domains: surgical efficiency, clinical-functional outcomes, and long-term biomechanical complications.

Surgical and Economic Efficiency of the VSP/CAD-CAM Protocol

The analyzed data confirms that the integration of Virtual Surgical Planning (VSP) and additive manufacturing (SLM printing from Ti-6Al-4V alloy) markedly optimizes the intraoperative phase:

Reduction in Operative Time: The deployment of customized osteotomy templates (cutting guides) and prefabricated PSIs decreases total time spent in the operating theater by **15% to 35%** (an average savings of 60–90 minutes). This directly minimizes intraoperative blood loss and risks related to prolonged general anesthesia.

Positioning Accuracy: Superimposition methods comparing pre- and postoperative CT models demonstrate bone segment and implant positioning deviations within **less than 1.0–1.5 mm**, an accuracy level unachievable via conventional, manual plate bending.

Clinical and Functional Outcomes

Isolated alloplastic reconstruction using PSIs—particularly relevant in cases of aggressive benign tumors like ameloblastoma or in medically compromised oncological patients—demonstrated the following results:

Elimination of Donor-Site Morbidity: Forgoing the traditional gold standard (the vascularized free fibula flap) eliminates wound defects at the donor site (e.g., fibula, iliac crest), lowering early postoperative complication rates by **25% to 30%**.

Occlusal Restoration: Rigid fixation of the PSI to the remaining condylar and coronoid processes enables the achievement of primary bite stability and central jaw relation in **92% to 95%** of patients during the early postoperative period.

Biomechanical Limitations and Long-Term TMJ Alterations

A deeper analysis of long-term outcomes (follow-up periods spanning 12 to 24 months) revealed distinct pathophysiological consequences linked to rigid monolithic fixation:

Stress Shielding Phenomenon: The modulus of elasticity of medical-grade titanium (approx. 110 GPa) substantially exceeds that of native cortical bone (15–20 GPa). The implant absorbs up to **80% to 90%** of the functional masticatory load. Lacking physiological strain stimulation, the host bone surrounding the fixation screws undergoes localized resorption, predisposing the hardware to micro-instability.

Condylar Unit Pathology: Longitudinal computed tomography and Finite Element Analysis (FEA) at the 1-year postoperative milestone systematically document structural remodeling of the temporomandibular joint (TMJ):

Displacement of the mandibular head within the glenoid fossa (lateral or distal translation) due to the complete lack of micro-mobility in the rigid implant assembly during mastication.

Asymmetrical joint space narrowing and progressive flattening (remodeling) of the condyle.

Gradual onset of joint-related syndromes (clicking, jaw deviation, restricted interincisal opening) particularly pronounced in young, functionally active individuals.

Discussion

When looking at the results of our literature analysis, we are faced with a very clear, yet challenging clinical paradox. On one hand, virtual surgical planning (VSP) and 3D-printed patient-specific implants (PSIs) have completely transformed how we approach mandibular reconstruction after tumor resection. If we look back at the traditional methods, a surgeon had to spend valuable intraoperative time manually bending reconstruction plates, often relying purely on visual estimation to restore the patient's facial symmetry. Today, CAD/CAM technologies give us a level of precision that was simply unimaginable a couple of decades ago.

However, the core issue that caught our attention during this review is what happens to these implants in the long term, especially in young, active patients. In an elderly patient with an aggressive carcinoma, where the primary goal is just to quickly bridge a massive defect and minimize time under general anesthesia, a rigid titanium PSI is an excellent "salvage" option. But if we take a 22-year-old female patient with a mural-type unicystic ameloblastoma—a benign but locally destructive tumor [3]—the clinical priorities change drastically. She has decades of functional life ahead of her.

Our findings show that while isolated alloplastic reconstruction (using a PSI without a free bone flap) successfully avoids donor-site morbidity from the leg or hip, it creates a severe biomechanical ticking time bomb for the temporomandibular joint (TMJ). The data we gathered systematically highlights that within 12 to 24 months post-op, a staggering 20% to 35% of these patients start showing signs of TMJ dysfunction, condylar displacement, or structural remodeling.

Why does this happen? We believe the answer lies in basic materials science and joint kinematics. Human bone is dynamic; it flexes, remodels, and adapts under stress according to Wolff's law. When we replace a large segment of the mandible with a monolithic piece of 3D-printed titanium, we are inserting a material with a modulus of elasticity (110 GPa) that is roughly six times stiffer than native cortical bone (15–20 GPa). This triggers a massive "stress shielding" effect. The ultra-rigid titanium plate absorbs almost all the chewing forces, leaving the remaining bone segments underloaded. Over time, the bone around the fixation screws begins to resorb, leading to micro-instability.

Even more critical is what happens to the condylar unit. In a healthy jaw, the mandible acts as a single, flexible arc. When a patient chews, there is a tiny amount of physiological micro-mobility and deformation across the mandibular body that helps cushion the forces hitting the joint. A monolithic PSI completely eliminates this natural buffering mechanism. The rigid plate acts as a lever, transferring unmitigated, raw mechanical torque directly up into the condylar head. Under general anesthesia, the surgical team might position the condyle perfectly inside the glenoid fossa on the operating table. But once the patient wakes up, starts swallowing, speaking, and chewing, the heavy, asymmetric pull of the masticatory muscles forces the rigid assembly into a new, unphysiological position.

This perfectly explains why at the 1-year milestone, follow-up radiographs and orthopantomograms so frequently reveal a distinct flattening of the condyle, joint space narrowing, or forced translation within the fossa. The joint is literally trying to remodel itself to survive the relentless mechanical overload.

What can we, as future clinicians, learn from this? In our opinion, these results mean we cannot view mandibular reconstruction as a purely geometric problem. It is not enough to just make a plate that "fits the gap" perfectly on a computer screen. We need to start thinking about the functional, dynamic life of the implant.

Conclusion

In conclusion, our literature review demonstrates that patient-specific implants (PSIs) represent a massive leap forward in craniomaxillofacial oncology. The integration of CAD/CAM technologies and virtual surgical planning (VSP) effectively solves incredibly complex geometric problems. They provide near-perfect anatomical accuracy, restore facial symmetry, and, crucially, save valuable intraoperative time by eliminating the need to manually bend standard plates at the operating table. For young patients dealing with aggressive but benign tumors like ameloblastoma, this approach offers an excellent path to avoid the heavy physical trauma and donor-site morbidity that comes with free bone flaps.

However, the long-term data gathered in this review proves that we cannot treat mandibular reconstruction as a purely engineering or cosmetic issue. It is simply not enough to close a bone defect with a beautiful titanium mesh that fits perfectly on a computer screen. The monolithic rigidity of 3D-printed titanium runs directly against live biology and joint kinematics. Due to the stress shielding effect and the complete loss of the mandible's natural flexibility, the relentless mechanical forces of chewing are transferred straight up into the temporomandibular joint. The flattening of the condylar head, joint space narrowing, and forced translation within the glenoid fossa observed just one year post-op are the logical reactions of a joint trying to survive an artificial mechanical lever.

Moving forward, if we want to reduce this 20% to 35% complication rate, surgeons and biomedical engineers must collaborate even more closely. Reconstructive protocols should routinely implement patient-specific Finite Element Analysis (FEA) to simulate actual muscle loads during the design phase. Clinically, early gnathological rehabilitation, protective occlusal splints, and targeted physical therapy must become standard post-operative care from the very first months. A patient-specific implant needs to be more than just anatomically customized; it must adapt to the dynamic reality of the human jaw so that immediate aesthetic success does not eventually cost a young patient their long-term quality of life.

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