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REVIEW ARTICLE

Contemporary zygomatic implant rehabilitation: A critical review of the evidence and clinical recommendations

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Abstract

Background: Zygomatic implant (ZI) therapy has evolved over the past two decades into an established modality for the rehabilitation of the severely atrophic maxilla, avoiding extensive bone augmentation procedures.

Aim: While the efficacy of ZI therapy is well established, variability in its clinical implementation and remaining knowledge gaps continue to influence its application in clinical practice.

Methods: This critical review, based on a focused PubMed/MEDLINE search, synthesized higher-level and long-term evidence on surgical approaches, loading protocols, indications and outcomes, complications, prosthetic considerations, digital workflows, and current consensus recommendations.

Results: Current evidence demonstrates favorable long-term survival across a broad range of ZI indications. The Quad Zygoma Protocol has further expanded graftless rehabilitation for the severely atrophic edentulous maxilla. Surgical approach selection should be guided by maxillozygomatic anatomy and prosthetically driven planning, while digital technologies have progressively shifted ZI surgery toward precision-oriented workflows. Nevertheless, heterogeneous complication profiles, inconsistent definitions of treatment success, and limited reporting of patient-reported and long-term biological and prosthetic outcomes remain important limitations.

Conclusions: Contemporary ZI rehabilitation represents an established treatment modality for complex maxillary rehabilitation, with the current focus shifting from demonstrating efficacy toward improving treatment predictability and long-term outcomes.

Clinical Recommendations: Appropriate case selection is fundamental to successful ZI rehabilitation. Surgical planning should integrate anatomical feasibility, implant emergence, and restorative design, while structured maintenance and patient compliance support long-term success. Digital workflows can enhance surgical accuracy and reproducibility but require surgical experience and clinical judgment.

KEYWORDS
atrophic maxilla, digital workflow, edentulous, full-arch rehabilitation, Quad Zygoma, zygomatic implant

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1 | INTRODUCTION

Rehabilitation of the severely atrophic maxilla remains one of the most challenging scenarios in implant dentistry. Conventional approaches based on extensive bone augmentation are associated with increased surgical morbidity, prolonged treatment time, higher cost, and, in some cases, unpredictable outcomes. These limitations have driven the development of graftless solutions, among which zygomatic implants (ZIs) represent a viable alternative for anchorage in the zygomatic bone in patients with severe maxillary atrophy.[1]

Since their introduction by Per-Ingvar Brånemark in the late 1980s, ZIs have evolved from a solution for maxillary defects to a comprehensive treatment modality for full-arch rehabilitation in patients with severe maxillary atrophy.[2] Early clinical studies demonstrated favorable long-term outcomes with high survival rates, although these protocols were surgically demanding and associated with variability in technique and outcomes.[1,3–5]

Over the past two decades, ZI therapy has undergone significant refinement, with improvements in surgical approaches and loading protocols enhancing functional rehabilitation and expanding clinical applicability.[6–9] Despite these advances, ZI therapy remains technically demanding and is associated with a spectrum of biological and mechanical complications. Importantly, variability in surgical techniques, treatment strategies, and prosthetic designs continues to contribute to heterogeneity in reported outcomes.

While high survival rates are consistently reported, the clinical application of ZI therapy remains insufficiently standardized.[10,11] Critical aspects, including complication profiles, patient-reported outcomes, and definitions of treatment success, are inconsistently reported and, in some cases, remain controversial. Increasingly, the challenge is no longer whether ZI therapy works, but how to deliver it consistently across diverse clinical scenarios.

Therefore, this review aims to critically appraise the current evidence on ZI therapy for the rehabilitation of the severely atrophic maxilla, focusing on surgical approaches, loading protocols, clinical indications, long-term outcomes, complications, digital technologies, and consensus guidelines. In addition, it seeks to identify existing gaps and outline future research directions and proposed clinical recommendations.

2 | REVIEW METHODOLOGY

This critical review was based on a focused PubMed/MEDLINE search of literature published between 2000 and 2026, prioritizing systematic reviews, consensus statements, comparative and prospective studies, and retrospective studies with ≥5 years of follow-up for long-term clinical outcomes. Shorter-term, technical, biomechanical, and preclinical studies were included where relevant. Evidence was critically synthesized according to study design, follow-up, consistency, and clinical relevance. ChatGPT (OpenAI) was used only for English-language and editorial refinement; all AI-assisted content was critically reviewed and revised by the authors, who take full responsibility for the final manuscript.

3 | THE EVOLUTION OF SURGICAL APPROACHES AND MANAGEMENT OF COMPLICATIONS

Over the past decades, surgical approaches for ZI placement have undergone a significant conceptual evolution, moving from standardized technical protocols toward anatomically and prosthetically driven strategies.[12] This progression reflects a broader shift from a surgeon-centered, technique-based approach to a more flexible strategy integrating biological and prosthetic considerations.

The original technique described by Per-Ingvar Brånemark represented an intra-sinus pathway for ZI insertion (Figure 1A).[1] Based on a Le Fort I vestibular access, elevation of a mucoperiosteal flap, and the creation of a lateral antrostomy, this approach allowed visualization of implant placement from the alveolar crest to the zygomatic body through the sinus cavity. Long-term results have demonstrated high survival of ZIs[1]; however, the intra-sinus pathway is associated with biological complications, such as sinusitis,[10] as well as prosthetic challenges related to a more palatal implant emergence and the resulting restorative contour.[13]

Sinusitis remains one of the most frequently reported biological complications of ZI rehabilitation, with systematic reviews reporting an incidence of approximately 10–20%.[10,11] A higher occurrence has been reported with the intra-sinus pathway, although the etiopathogenesis remains incompletely understood. Proposed contributing factors include disruption of the Schneiderian membrane, mucosal

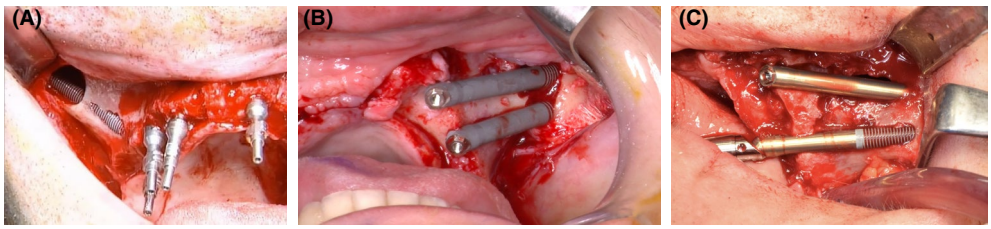


FIGURE 1 (A) Right posterior ZI placed through an intrasinus pathway in a flat or convex maxillary sinus anatomy. (B) Both ZIs were placed through an extrasinus pathway in a maxillary sinus with pronounced concavity. (C) Both ZIs were placed through a sinus-wall pathway in a maxillary sinus with mild concavity.

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thickening, foreign-body reactions, and pre-existing sinus conditions.[14,15] Nevertheless, ZI failure secondary to sinusitis appears uncommon, and most cases can be managed conservatively or, when necessary, by functional endoscopic sinus surgery (FESS).[16]

Beyond sinusitis, other sinus-related complications include oroantral communication and fistula formation. Although less frequently reported, these complications are clinically relevant and may be associated with unfavorable implant positioning, inadequate soft-tissue sealing, and persistent sinus inflammation. Appropriate implant trajectory and soft-tissue management are therefore important preventive considerations. Established cases may require surgical closure using a connective tissue graft or buccal fat pad flap, with otorhinolaryngology involvement when associated sinus disease is present.[11]

These biological and prosthetic limitations contributed to the development of alternative trajectories aimed at reducing sinus involvement and improving implant emergence. The extra-sinus approach represented an important step in this evolution, positioning most of the ZI body outside the sinus cavity and adapting its trajectory to the morphology of the lateral maxillary wall and alveolar crest (Figure 1B).[7,17–18]

While this may facilitate a more favorable prosthetic emergence, the implant head is often positioned outside the alveolar crest, especially when the extramaxillary technique is used in cases with a convex sinus wall.[18] This buccal positioning may compromise hard- and soft-tissue support around the coronal portion of the ZI. Accordingly, a systematic review has shown that soft-tissue recession around the coronal portion of the ZI represents another area of concern in the extra-sinus pathway.[16] The authors' clinical experience is consistent with this observation, particularly when the coronal portion of the implant is excessively buccally positioned or lacks adequate soft-tissue coverage. Therefore, the prosthetic advantages of a more favorable emergence should be balanced against the potential risk of soft-tissue complications.

Various strategies have been proposed to address these complications, although their clinical effectiveness remains insufficiently established. Uncertainty remains regarding the optimal timing of soft-tissue grafting, whether performed simultaneously with ZI placement or after the development of dehiscence. More recently, modified ZI macrodesigns, including threadless implant bodies and different coronal geometries, have been introduced with the aim of reducing soft-tissue compression and local inflammation.[19,20] However, long-term clinical evidence supporting these strategies remains limited.

In intermediate anatomical configurations, the ZI trajectory may partially engage the lateral sinus wall. The sinus-slot technique exemplifies this transitional pathway, using a groove in the lateral sinus wall to guide implant placement while preserving partial bony support[6,8] (Figure 1C). A key feature of this approach is the creation of a groove in the lateral sinus wall to guide the ZI trajectory, potentially increasing radiographic bone-to-implant contact[21] while reducing the need for a formal sinus window and facilitating a more favorable crestal emergence profile. However, current systematic-review evidence does not establish the superiority of any single pathway; rather, the balance between potential benefits and complications appears to depend primarily on individual maxillozygomatic anatomy and implant positioning.[16]

These observations progressively shifted the emphasis from selecting a predefined surgical pathway toward anatomy-guided trajectory selection. In 2010, Davó et al. provided early prospective clinical evidence of this principle, describing a decision-making process in which ZI positioning was determined according to the anatomy of the zygoma and surrounding structures[22], with the implant pathway selected inside or outside the maxillary sinus according to patient-specific anatomy, particularly the curvature of the lateral maxillary wall.[22,23]

More recently, the term "Anatomy-Guided Approach" (AGA) was adopted within the 2023 International Team for Implantology (ITI) consensus framework and its supporting systematic review to describe anatomy-guided ZI placement across established surgical trajectories.[16,24] Within this framework, anatomy-guided placement encompasses trajectories ranging from intrasinus to sinus-wall and extrasinus pathways, with the appropriate pathway selected according to patient-specific maxillozygomatic anatomy (Table 1). Accordingly, AGA is best understood not as an additional surgical trajectory, but as an overarching framework for anatomy-guided selection among established ZI trajectories.[12]

An important parallel development in this evolution was the Zygoma Anatomy-Guided Approach (ZAGA) classification introduced by Aparicio et al. in 2011,[25] which categorized maxillozygomatic anatomy into five configurations (ZAGA 0–4) and related them to corresponding ZI trajectories. While providing a structured framework for translating anatomical variability into clinical pathways, the classification reduces a continuous three-dimensional anatomical spectrum into five discrete categories, highlighting the potential challenge of classifying intermediate anatomical configurations.

ZAGA subsequently evolved beyond this anatomical classification into the broader ZAGA Concept, incorporating surgical, prosthetic, and tissue-management principles.[26,27] Although this expansion provides a more comprehensive framework for ZI rehabilitation, its individual components are supported by varying levels of evidence, and long-term clinical validation of the ZAGA Concept as an integrated framework remains limited.

While advances in anatomy-guided trajectory selection have largely focused on the relationship between the ZI body and the maxillary sinus, the position of the apical portion of the implant relative to the external surface of the zygomatic bone represents another important anatomical consideration. Although long-term clinical observations suggest minimal zygomatic bone resorption around ZIs after more than 10 years of functional loading,[28] excessive implant protrusion beyond the external surface of the zygoma has been associated with peri-zygomatic infection and, less frequently, cutaneous fistula formation in retrospective clinical studies.[29,30] When a cutaneous fistula develops as a consequence of excessive apical protrusion, surgical removal of the ZI apex protruding beyond the external surface of the zygomatic bone may be indicated.[16,31]

Orofacial inflammation represents another relevant biological complication of ZI rehabilitation, with incidences of 23.8% and 35.7% reported in individual studies.[31,32] However, the absence of standardized

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definitions and consistent reporting limits meaningful comparison across studies, and its relationship with implant trajectory, design, and prosthetic factors remains unclear. The main biological complications associated with ZI rehabilitation and their corresponding management considerations are summarized in Table 2.

4 | PROSTHETIC CONSIDERATIONS AND TREATMENT SUCCESS

In patients with severe maxillary atrophy, the ZI head frequently cannot coincide with the ideal tooth position because implant

TABLE 1 Characteristics of ZI trajectories within the Anatomy-Guided Approach (AGA).

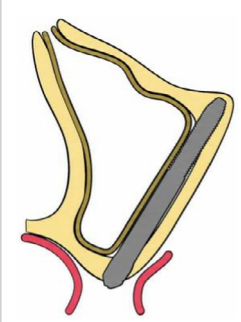
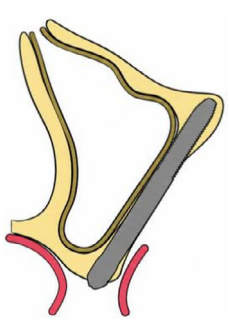
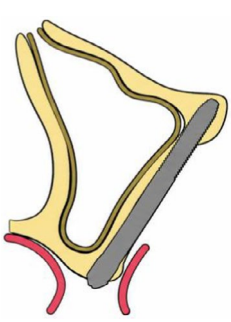
Trajectory	Intrasinus	Sinus-wall	Extrasinus
			
Representative technique	Brånemark classic technique[1]	Sinus-slot technique, Chow's technique[6,8]	Extrasinus/extramaxillary techniques[7,17–18]
Lateral maxillary wall morphology	Relatively flat/minimal concavity	Mild–moderate concavity	Pronounced concavity
Implant trajectory	Predominantly trans-sinus	Partially engages the lateral sinus wall	Predominantly extrasinus
Surgical characteristics	Lateral antrostomy; Schneiderian membrane elevation; trans-sinus osteotomy	Lateral sinus-wall groove/slot; localized Schneiderian membrane elevation; osteotomy along the lateral sinus wall	Osteotomy predominantly along the external aspect of the lateral maxillary wall; limited sinus-wall and Schneiderian membrane manipulation
Main considerations	Greater sinus involvement; risk of sinus-related complications	Partial lateral-wall engagement; reduced sinus involvement	Reduced sinus involvement; potential buccal positioning with soft-tissue dehiscence/recession

TABLE 2 Biological complications and management considerations in ZI rehabilitation.

Complication	Main contributing factors	Prevention/management
Maxillary sinusitis	Sinus involvement; membrane alteration; pre-existing sinus disease[10,11,16]	Preoperative sinus assessment and appropriate trajectory; conservative treatment or FESS for persistent cases[10,11,14–16]
Oroantral communication/fistula	Unfavorable implant position; inadequate soft-tissue sealing; persistent sinus inflammation[10,11,33]	Appropriate positioning and soft-tissue closure; treat associated sinus disease; surgical closure when persistent[10,11,33]
Soft-tissue recession/dehiscence	Buccal implant position; inadequate tissue coverage; difficult hygiene access[16,31]	Optimize emergence and tissue coverage; improve hygiene access; consider soft-tissue augmentation[16,18]
Peri-zygomatic infection/cutaneous fistula	Excessive zygomatic protrusion; local infection[28–30]	Avoid excessive apical protrusion; infection control and surgical management when required[28–30]
Orofacial inflammation	Multifactorial; potential relationship with implant trajectory, design, and prosthetic factors remains unclear[31,32]	Identification and management of the underlying inflammatory or infectious source; management should be individualized according to clinical findings[31]
Peri-implant mucosal inflammation	Plaque accumulation; unfavorable emergence; limited hygiene access	Hygiene-accessible prosthetic design and regular professional maintenance[21]

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placement is constrained by the residual maxillary anatomy, the surrounding soft-tissue conditions, and the need to achieve adequate and safe zygomatic anchorage.[34] Consequently, some degree of discrepancy between implant emergence and the intended restorative position is often unavoidable. Pre-surgical planning should therefore establish the intended tooth position first and, within anatomical, biological, and surgical constraints, select an implant trajectory that minimizes this discrepancy while maintaining appropriate zygomatic anchorage. The intended tooth position serves as a prosthetic reference, although positioning the implant head directly beneath it may not always be achievable. As illustrated in Figure 2A–D, even with an extra-sinus trajectory, the implant head may remain palatal to the intended tooth position when further buccal placement is limited by the available alveolar anatomy and soft-tissue boundary. Prosthetically driven ZI placement therefore requires a balance between the desired restorative position and anatomical and biological feasibility.

A more palatal implant emergence, resulting from the underlying maxillary anatomy and/or the selected implant trajectory, may require a bulkier palatal prosthetic contour and has been associated in some reports with difficulties in speech and patient comfort.[13] However, these effects have not been consistently demonstrated across clinical studies, and the available evidence does not establish a clear relationship between palatal emergence and patient-reported functional or phonetic impairment.[33,35] In the authors' clinical experience, the absence of a consistent relationship appears to more closely reflect clinical reality. Nevertheless, a more palatal emergence and the resulting prosthetic contour may complicate hygiene access and maintenance, potentially contributing to plaque accumulation and peri-implant mucosal inflammation.[16]

An additional prosthetic consideration is the orientation of the ZI platform itself. Many ZI systems incorporate an angulated restorative platform, commonly ranging from approximately 45° to 55°, to accommodate the marked difference between the ZI trajectory and the restorative axis.[36] Consequently, planning should consider not only the three-dimensional position of the implant head but also the rotational orientation of the restorative platform at the time of implant placement. Appropriate orientation of the platform toward the anticipated restorative pathway may reduce the degree of prosthetic correction subsequently required.[36] From this perspective, accurate positioning and orientation of the implant platform at the time of surgery may be at least as important as the subsequent selection of intermediate-abutment angulation or height. Abutments can redirect the screw-access channel but cannot fully compensate for an unfavorable three-dimensional position of the implant head (Figure 2D).

Severe maxillary atrophy creates a distinct prosthetic challenge, as the restoration must compensate for substantial hard- and soft-tissue loss and the discrepancy between implant emergence and the intended tooth position.[36] The extent of tissue deficiency may require a fixed prosthesis type 2 (FP-2) restoration, while the more extensive defects commonly associated with Quad Zygoma rehabilitation often require a fixed prosthesis type 3 (FP-3) design.[37] Restorative options include acrylic- or composite-based prostheses with titanium frameworks, monolithic zirconia, and combination designs, although evidence supporting the superiority of any specific material remains limited.[38] Implant-supported overdentures may also represent an alternative prosthetic option in selected patients, although only a limited number of studies have reported their long-term outcomes in ZI rehabilitation.[39] Future studies should further evaluate intermediate-abutment design and height, framework design and load distribution, restorative materials, and emergence-related prosthetic, maintenance, patient-reported, and phonetic outcomes.

However, outcome assessment using existing ZI success criteria remains limited. Existing ZI success criteria incorporate different combinations and interpretations of biological, prosthetic, and clinical parameters.[9,40–41] The ORIS criteria represent an important

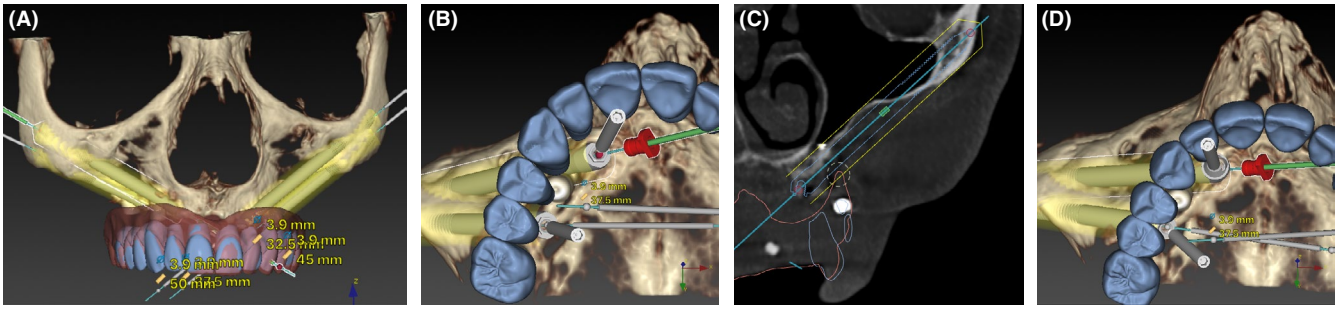


FIGURE 2 (A) A quad zygoma case following failed implant treatment was planned using a double-scan protocol. The existing overdenture/prosthetic setup is shown in red, and the virtual tooth arrangement derived from this setup is shown in blue. (B) The right anterior zygomatic implant (#12) is positioned with its implant head centrally within the available alveolar crest, although it remains palatal to the corresponding prosthetic tooth position. (C) The implant follows an extra-sinus trajectory; however, its crestal position remains anatomically constrained (white circle), as the implant body (blue) already lies close to the inner, tissue-facing surface of the existing overdenture (red), approximating the soft-tissue boundary. Any further buccal displacement would therefore increase soft-tissue compression and potentially the risk of subsequent soft-tissue recession. (D) Although an angled abutment can redirect the screw-access channel toward a more favorable prosthetic emergence, it does not change the position of the implant head or its spatial relationship to the prosthetic tooth. Thus, the underlying implant–tooth discrepancy remains unchanged, and a bulkier palatal restoration may still be required to compensate for this discrepancy.

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attempt to distinguish ZI success from mere implant survival by incorporating prosthetic positioning, rhinosinus status, soft-tissue conditions, and implant stability.[40]

ZI mobility represents another area of uncertainty in defining success. While rotational mobility is generally regarded as an indicator of failure, slight lateral mobility has been interpreted differently and may still be considered compatible with clinical success in the absence of rotation.[9,40–41] From a biomechanical perspective, this may be explained by the predominant anchorage of ZIs within the zygomatic bone, while the long extra-zygomatic portion of the implant may have limited or no direct bone contact; this concept is also reflected in contemporary ZI designs incorporating partially threaded or threadless implant bodies.[19,20] Importantly, ZI mobility itself remains difficult to quantify objectively, with different assessment methods and no standardized quantitative thresholds for lateral movement. Therefore, although ORIS provides a useful standardized framework for evaluating ZI success, further studies are needed to establish the clinical validity and reproducibility of its proposed criteria and thresholds.[40] Similarly, postoperative sinus radiographic changes do not necessarily indicate clinically relevant rhinosinus disease, particularly in asymptomatic patients. Distinguishing radiographic abnormalities from clinically diagnosed rhinosinusitis and disease requiring intervention is therefore important.

Accordingly, in this review, predictability is defined as the reproducibility of favorable outcomes over time, encompassing implant and prosthetic survival, biological and prosthetic complications, and maintenance of function. High implant survival alone should not be interpreted as evidence of predictable treatment, particularly when success criteria and complication reporting remain heterogeneous across studies.[9,40–41] Claims of predictability throughout this review are therefore interpreted in relation to the consistency, duration, and multidimensional nature of the supporting clinical evidence.

5 | THE TRANSITION OF LOADING PROTOCOLS AND NORMALIZATION OF QUALITY OF LIFE

In patients with edentulous maxillae, achieving early functional and prosthetic rehabilitation represents a key clinical objective, as it supports the normalization of quality of life through timely restoration of function, esthetics, and social confidence.[42] The original loading protocol for ZI rehabilitation was therefore based on a two-stage surgical approach with delayed loading, reflecting the biological principles of early osseointegration and a cautious approach to functional integration.[1,2] Over time, accumulating clinical experience and advances in ZI design, surface technology, and prosthetic concepts have led to a progressive shift toward immediate loading strategies.[12]

Early development of immediate loading in ZI rehabilitation was driven by pioneering clinical work from Chow, Davó, and Bedrossian in the mid-2000s.[43–45] This principle is particularly relevant in the context of the Quad Zygoma protocol, where the distribution of forces across a full-arch framework enhances the overall mechanical stability of the system. Finite element analyses further support this concept, demonstrating more favorable stress distribution in splinted configurations compared to non-splinted conditions.[46]

Rigid splinting of ZIs reduces micromovement and optimizes load distribution, thereby decreasing reliance on high insertion torque as the sole indicator of stability.[46] This supports a more integrated concept of implant stability, in which surgical anchorage and prosthetic reinforcement are interdependent. Long-term retrospective evidence further supports the feasibility of immediate loading, including implants inserted with relatively low torque values, although these observations remain derived predominantly from observational cohorts.[31]

In this sense, immediate loading represents more than a temporal modification of the protocol, constituting a functionally driven treatment concept. A systematic review has demonstrated favorable outcomes, with immediate loading associated with higher survival rates (98.1% vs. 95%) and lower failure rates (1.7% vs. 3.1%) compared with delayed protocols.[10] However, this difference should be interpreted cautiously, as many delayed-loading cohorts originated from earlier phases of ZI development using different implant designs, surfaces, and restorative components.

Beyond these biomechanical considerations, the advantages of immediate loading are also reflected in patient-reported outcomes, particularly during the early phase of rehabilitation. A clinical study evaluating within-patient changes has also demonstrated significant improvements in patient-reported outcomes following immediate loading protocols.[47] Patient satisfaction and quality-of-life measures were significantly improved after treatment compared with preoperative baseline values, indicating a substantial positive impact of immediate functional rehabilitation on patient experience.[47] Additionally, compared with conventional implants following a staged approach with bone augmentation, a randomized controlled trial demonstrated a markedly reduced treatment timeline.[48] The mean time to functional prosthesis was markedly shorter in the ZI group (1.34 vs. 444.32 days), which may contribute to greater early patient satisfaction and faster functional recovery. The ZI group also required fewer clinical visits (15 vs. 20), indicating a lower overall treatment burden.

A recent review of patient-reported outcomes found consistently high patient satisfaction following ZI rehabilitation across both delayed and immediate loading protocols.[49] However, study heterogeneity and the lack of controlled comparisons preclude conclusions regarding the specific effect of loading strategy.

6 | INDICATIONS AND LONG-TERM OUTCOMES

6.1 | Maxillary defects

In patients with maxillary defects secondary to oncologic resection—particularly those corresponding to Brown Class II and III defects[50]—ZIs

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have demonstrated encouraging clinical outcomes, with reported survival rates ranging from 77% to 100%.[11,51–52] (Figure 3A–D) Notably, ZI failures tend to occur early, prior to prosthetic loading, suggesting that biological integration—rather than long-term functional loading—is the primary determinant of success in this cohort.[52] Several factors have been associated with an increased risk of implant failure, including tumor recurrence, prior or adjuvant radiotherapy, implant positioning, peri-implant soft-tissue conditions, and extensive defect morphology.[51,52] These factors may impair osseointegration, compromise biomechanical stability, or predispose to biological complications such as infection, sinusitis, or oroantral communication, which have been consistently reported in systematic reviews.[51]

Rehabilitation strategies traditionally include obturator-based prostheses or microvascular free flap reconstruction combined with delayed implant placement.[2] A comparative study has shown that while functional performance may be similar between these approaches, implant-supported fixed rehabilitation is associated with improvements in specific patient-reported domains, particularly psychological well-being and social aspects of quality of life.[54] However, these approaches are often associated with prolonged treatment timelines.

Beyond these delayed rehabilitation protocols, ZIs may also be incorporated into immediate reconstructive strategies. In particular, concepts such as the zygomatic implant perforated (ZIP) flap technique combine tumor resection, flap reconstruction, and implant placement, facilitating earlier prosthetic rehabilitation and reducing the need for staged procedures.[51,55] A clinical study has reported ZI and prosthesis survival rates exceeding 95%, with early functional rehabilitation achievable even in patients undergoing adjuvant radiotherapy.[55] However, this technique remains technically demanding, requiring multidisciplinary expertise and careful surgical–prosthodontic coordination, with digital technologies potentially supporting planning and execution.[56]

6.2 | Hybrid approach

ZIs were initially introduced as part of a hybrid treatment concept for the rehabilitation of the severely atrophic maxilla. In this original approach, one ZI was placed in each posterior maxillary region and combined with two to four anterior conventional implants to support a full-arch prosthesis.[1] This strategy was primarily indicated in patients with severe posterior maxillary resorption but sufficient residual bone in the anterior region, corresponding to Cawood and Howell Class V or VI.[57] Early clinical studies reported favorable outcomes, with implant and prosthetic survival exceeding 95% across short- and long-term follow-up,[1] while subsequent studies also documented the use of immediate loading.[44,58] (Figure 4A–F).

From a biomechanical perspective, combining ZIs with anterior conventional implants may provide more favorable stress distribution than configurations lacking anterior implant support, with cross-arch stabilization contributing to reduced bending forces and improved load transfer across the prosthesis.[59] Consistent with this rationale, a systematic review and meta-analysis found similarly high survival of ZIs and anterior conventional implants in fixed maxillary rehabilitation, although the available evidence was predominantly limited to follow-up periods of up to 10 years.[60]

However, evidence regarding long-term performance remains limited. In a retrospective cohort with a mean follow-up of 12.1 years, survival of anterior conventional implants placed in conjunction with ZIs progressively declined, reaching 67.7% at 20 years. Bruxism, overdenture loading, and implant length ≤10 mm were associated with poorer long-term outcomes.[61] When anatomically feasible, longer conventional implants should be preferred for hybrid ZI rehabilitation, while the use of short implants should be approached cautiously, particularly in patients with additional biomechanical risk factors.[61] Overall, anterior implants do not appear to represent an inherent weak point in the medium term, although their long-term performance remains less certain. Further studies should better define the indications for the hybrid approach according to anatomical, occlusal, and prosthetic factors.

6.3 | Quad Zygoma protocol

The extension of ZI therapy from a hybrid approach to completely ZI-supported rehabilitation reflects the increasing anatomical constraints associated with advanced maxillary atrophy.[38] When residual anterior bone is insufficient for conventional implant placement, the Quad Zygoma protocol, involving four ZIs to support full-arch rehabilitation, provides an alternative and was clinically described by Duarte et al.[62] By placing two ZIs on each side, the Quad Zygoma protocol eliminates the need for conventional anterior implants and provides a broader anterior–posterior distribution of prosthetic support, enabling immediate functional loading. Malevez and Davó

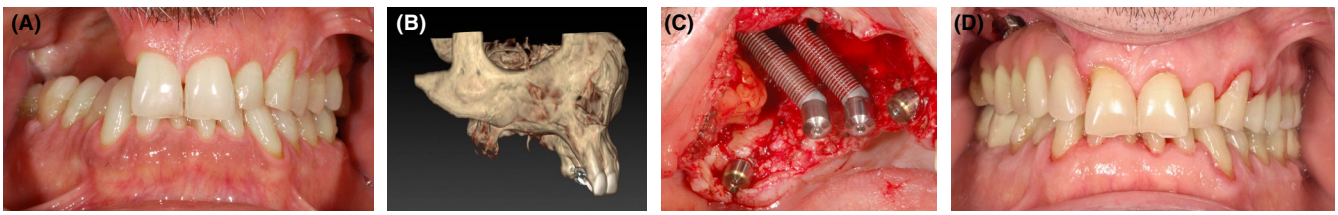


FIGURE 3 (A) Frontal view of a right maxillary defect following oncologic resection. (B) CBCT demonstrating a Brown Class II maxillary defect. (C) Rehabilitation performed using 2 ZIs combined with 2 conventional implants. (D) Ten-year postoperative follow-up demonstrating stable functional rehabilitation.[53]

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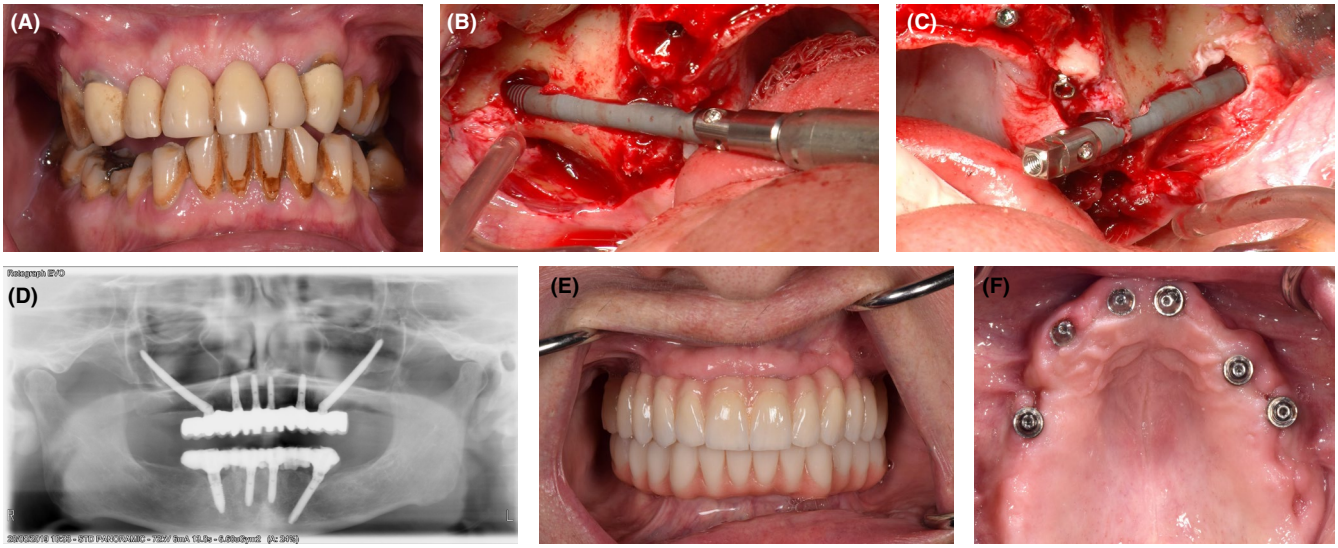


FIGURE 4 (A) Patient presenting with advanced periodontal disease requiring full-arch rehabilitation. (B) Immediate placement of a right posterior ZI in the second premolar region. (C) Immediate placement of a left posterior ZI in the second premolar region. (D) Hybrid ZI rehabilitation performed using bilateral posterior ZIs combined with 4 anterior conventional implants for full-arch restoration. (E) Twelve-year follow-up demonstrating stable prosthetic and peri-implant conditions, emphasizing the role of hygiene-accessible prosthetic design and long-term maintenance in sustaining peri-implant health. (F) Stable and healthy peri-implant soft-tissue conditions at long-term follow-up.

also independently contributed to the early clinical development of this approach, with reports dating to 2010.[22,63] Subsequent clinical studies further evaluated the Quad Zygoma protocol and expanded the evidence supporting its application in severely atrophic maxillae.[63–65] (Figure 5A–D).

A recent retrospective comparison found slightly higher implant survival with the Quad Zygoma than with the hybrid approach, while prosthesis survival was comparable between groups.[65] Systematic reviews similarly report pooled ZI survival of approximately 98%, although much of the available evidence remains limited to short- and medium-term follow-up.[64]

Long-term data also support favorable outcomes in complex rescue cases following failed full-arch rehabilitation due to peri-implantitis.[66] At a mean follow-up of 8.2 years, implant and prosthetic outcomes exceeded 95%, although sinusitis was more frequent than in conventional edentulous ZI cohorts. All cases were successfully managed without implant loss, supporting Quad Zygoma as a predictable rescue strategy while highlighting the need for further investigation of sinus complications.

Beyond implant survival, Quad Zygoma provides effective functional rehabilitation, with adequate posterior support achieved through functional cantilever extensions and favorable masticatory performance.[31] Accordingly, routine addition of pterygoid implants may not be necessary and should be guided by individual anatomical and prosthetic requirements.[67]

6.4 | Expanded indications

Although ZIs were initially used for severely atrophic edentulous maxillae, their indications have expanded to more selective and anatomically complex cases, including unilateral maxillary deficiency in partially edentulous patients (Figure 6A,B) and congenital craniofacial conditions where conventional implant therapy is limited by insufficient bone or previous treatment failure.[68] (Figure 6C–F).

In patients with severe unilateral maxillary resorption, treatment strategy is influenced by anatomical limitations, the need for immediate functional rehabilitation, and previous graft failure.[69] In this context, unilateral ZI placement combined with conventional implants provides a graftless strategy that enables immediate loading while preserving residual dentition and adjacent anatomical structures. Early reports established the feasibility of this approach,[2,58,70] while subsequent studies with follow-up exceeding 10 years demonstrated high implant survival and stable prosthetic outcomes.[69] More recently, Polido et al. synthesized the available evidence and further clarified the clinical indications for unilateral ZI rehabilitation.[68]

Additional patient groups include individuals with cleft lip and palate (CLP) and ectodermal dysplasia (ED), who may present with severe maxillary deficiency that limits conventional implant rehabilitation.[71,72] In CLP, emerging evidence supports ZIs as a graftless option that may reduce the need for additional reconstructive procedures.[71] Similarly, a systematic review of ED reported 47 ZIs in 22 patients without implant failure.[72] However, reduced inferior zygomatic thickness and insufficient zygomatic length have been reported in patients with ED,[73] potentially limiting the feasibility of Quad Zygoma rehabilitation and requiring careful anatomical assessment.

Across these indications, outcomes depend largely on patient selection, anatomical assessment, individualized treatment planning, and the timing of intervention. Further prospective long-term studies are needed to better define treatment protocols and indications.

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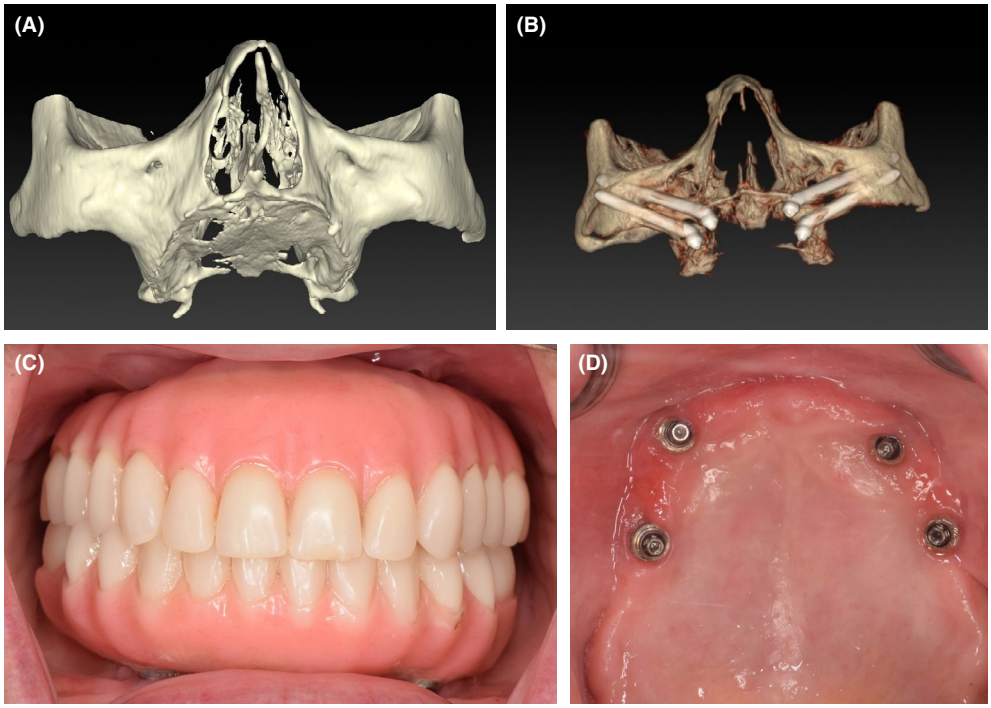


FIGURE 5 (A) CBCT demonstrating a severely atrophic edentulous maxilla. (B) Quad Zygoma protocol performed to support a fixed full-arch restoration. (C) An FP-3 type prosthesis was delivered to compensate for hard- and soft-tissue loss and to restore facial support. (D) Ten-year follow-up demonstrating stable peri-implant soft-tissue conditions.

7 | INTEGRATION OF DIGITAL TECHNOLOGIES AND CLINICAL RELEVANCE

The introduction of digital technologies has changed several aspects of ZI planning and placement. CBCT-based virtual planning allows the implant trajectory to be evaluated in relation to both the maxillary–zygomatic anatomy and the intended prosthetic position, while computer-assisted implant surgery (CAIS) provides different means of transferring this plan to the surgical field.[74]

Static computer-assisted implant surgery (s-CAIS) was among the first digital approaches used for ZI placement, with modified double-sleeve guides developed to improve control along the long osteotomy pathway.[75] A recent meta-analysis reported favorable accuracy with these modified guides,[76] although evidence remains largely based on small clinical cohorts and experimental studies. Manufacturing tolerances, limited mouth opening, and the inability to adjust the trajectory intraoperatively remain important limitations.

Dynamic computer-assisted implant surgery (d-CAIS) provides real-time visualization of drill position and trajectory relative to the preoperative plan.[75] In contrast to static guidance, the surgeon can adjust the entry point, angulation, or drilling strategy during surgery while maintaining navigational feedback (Figure 7A–C). This flexibility may be useful in ZI surgery, where relatively small changes in trajectory can affect zygomatic anchorage and prosthetic emergence. In a meta-analysis including 511 ZIs, pooled mean deviations for d-CAIS were 1.81 mm at the entry point, 2.95 mm at the apex, and 3.49° for angular deviation.[76] Accuracy is influenced by several technical and operator-related factors, including registration quality, tracker stability, line-of-sight, surgical experience, and drill stability along the planned trajectory during osteotomy. The number of fiducial markers has also been associated with precision, further highlighting the importance of the registration protocol.

These deviation values require careful clinical interpretation. They describe the difference between planned and placed implant positions but do not, by themselves, define whether placement is clinically safe. At present, no validated ZI-specific linear or angular threshold distinguishes acceptable from inaccurate or potentially unsafe placement. Although a safety margin of approximately 2 mm from critical anatomical structures is commonly recommended in conventional implant surgery,[77] this should not be interpreted as an acceptable amount of surgical deviation.

This distinction is particularly important for ZIs because of their long trajectory and proximity to critical anatomical structures, especially when pooled apical deviations reported for d-CAIS may exceed 2 mm.[76] The clinical relevance of a deviation therefore depends not only on its magnitude, but also on its direction and the remaining anatomical safety margin, particularly in relation to the orbit and infratemporal fossa. Although no penetration of critical structures was reported in the studies included in the review,[76] this absence of anatomical violations does not establish a numerical threshold for safe ZI placement.

Robotic computer-assisted implant surgery (r-CAIS) has more recently been investigated as another means of controlling ZI osteotomy and implant placement.[74,78] A systematic review and

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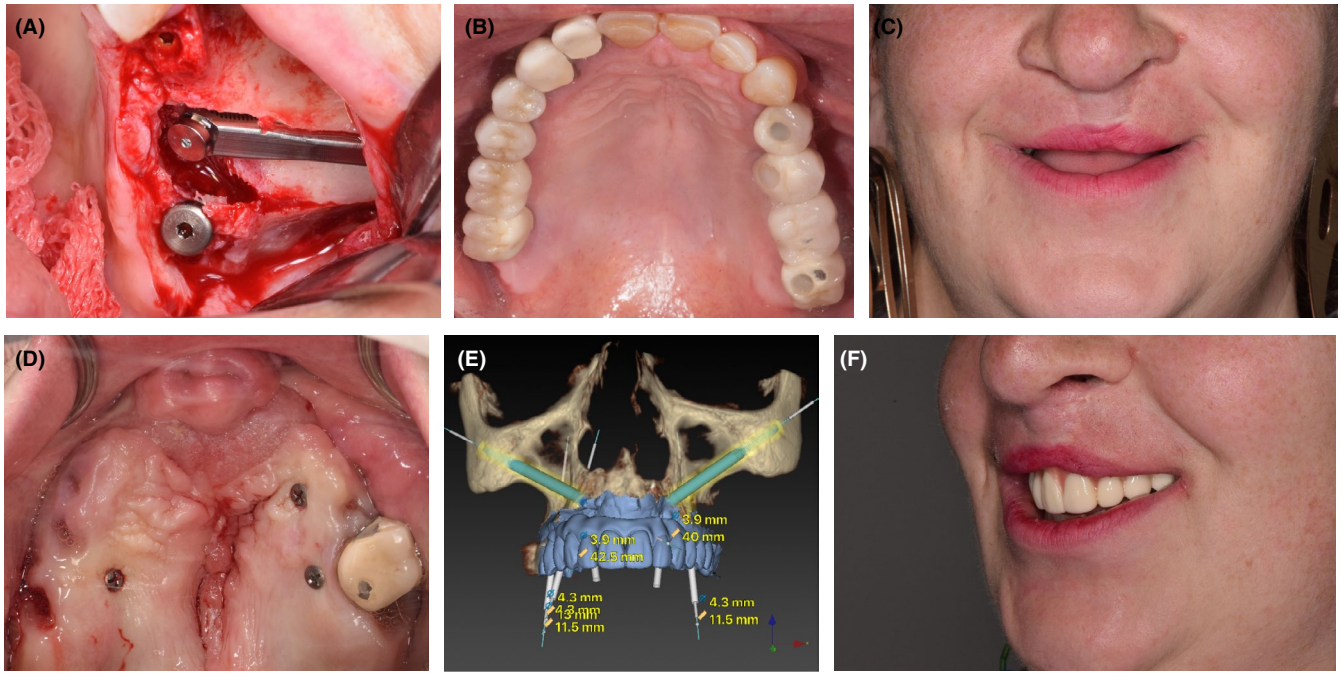


FIGURE 6 (A) Unilateral ZI placement performed in a partially edentulous maxilla following failed sinus augmentation. (B) One posterior ZI in the second premolar region combined with 2 conventional implants in the first premolar and second molar regions. (C) Patient with cleft lip and palate previously treated with cheiloplasty, palatoplasty, and secondary bone grafting. Progressive tooth mobility resulted in complete edentulism and failure of conventional rehabilitation. (D) Occlusal view demonstrating congenital anterior maxillary deficiency. Three mini-screws were placed for navigation-based registration. (E) Virtual implant planning demonstrating bilateral anterior ZIs combined with 4 conventional implants in the maxillary defect. Navigation-assisted planning optimized implant trajectory, screw-access positioning, multi-unit abutment correction, and prosthetic emergence profile. (F) Immediate functional loading was delivered within 24 h postoperatively.

meta-analysis including 185 ZIs reported pooled deviations of 1.04 mm at the entry point, 1.47 mm at the exit point, and 1.22° for angular deviation.[79] These pooled estimates were numerically lower than those reported for d-CAIS, particularly for apical/exit and angular deviations, suggesting the potential for improved trajectory control at the zygomatic anchorage zone.[76] Artificial intelligence (AI) is also being investigated for ZI treatment planning. Automated planning systems have generated implant trajectories according to predefined anatomical and biomechanical constraints, with the potential to reduce planning complexity and inter-operator variability.[80,81] Quantitative optimization approaches have also reported greater bone–implant contact than manually planned trajectories.[82] Nevertheless, the evidence for r-CAIS and AI in ZI therapy remains limited, with much of the published work consisting of in vitro, hybrid, or early feasibility studies.

The clinical value of digital technology extends beyond reducing placement deviation. Accuracy is meaningful only when the planned implant position is appropriate and based on sound anatomical and prosthetic principles.[83] In ZI surgery, digital technologies may therefore improve the reproducibility of transferring an anatomically safe and prosthetically driven plan to the patient,[84] but do not replace treatment planning, surgical experience, or clinical judgment. As current evidence remains focused largely on technical accuracy, future studies should determine whether greater precision translates into improved safety, fewer complications, better patient- and clinician-reported outcomes, and improved implant, prosthetic, and long-term treatment success.

8 | CURRENT CONSENSUS STATEMENTS AND GUIDELINES

Over time, ZI therapy has evolved from a technique-driven approach into an increasingly evidence- and consensus-informed clinical strategy, although debate persists regarding its indications and clinical application. The ITI and Global Consensus statements largely agree on the use of ZIs for rehabilitation of the severely atrophic maxilla.[24,85] The ITI Consensus provided evidence-based recommendations on indications and outcomes, while the Global Consensus addressed broader clinical aspects, including specialized training, CBCT-based planning, and systematic assessment of the maxillary sinus.

Both consensus statements emphasize that ZI therapy should be performed by clinicians with advanced training and experience. While the Global Consensus explicitly reports strong agreement on this requirement,[85] the ITI Consensus reflects it through the procedural complexity and need for careful case selection.[24] Accordingly, ZI placement should be regarded as a highly specialized procedure rather than a routine intervention. The authors further emphasize the importance of structured education and training programs to provide early-career

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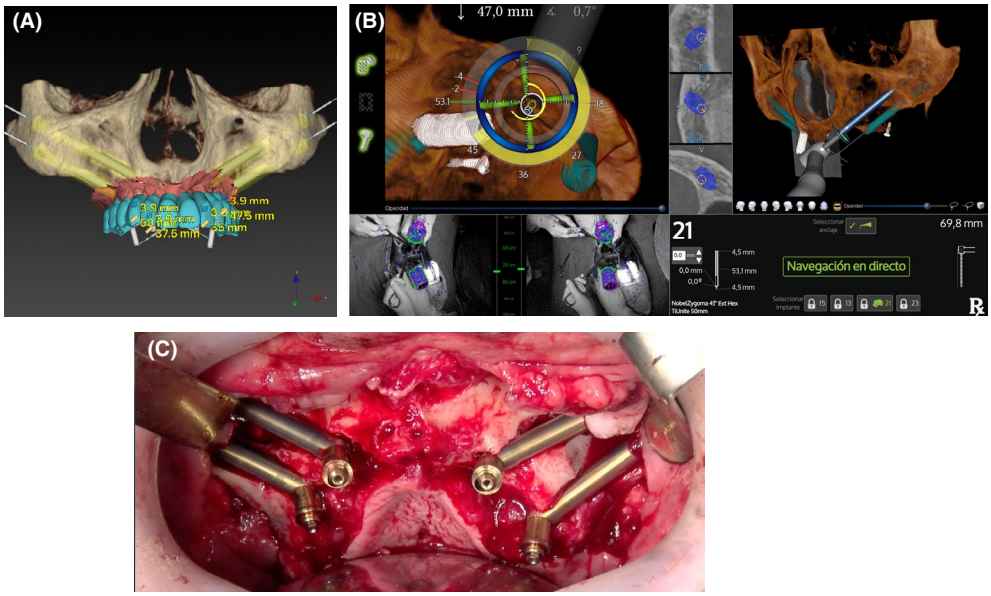


FIGURE 7 (A) Prosthetically driven virtual planning of Quad Zygoma rehabilitation. Safe margins were established from the orbital rim and between adjacent ZIs during virtual planning. Multi-unit abutments were selected to correct implant angulation and establish a common restorative path of insertion. (B) Real-time dynamic navigation enabled continuous tracking of the surgical instrument during osteotomy preparation, while providing real-time deviation feedback relative to the planned implant trajectory. (C) Quad Zygoma placement performed under real-time dynamic navigation guidance.

clinicians entering the field with progressive, competency-based pathways for developing expertise in ZI rehabilitation.

These developments indicate that ZI therapy has transitioned from a technique-driven to an evidence-supported and increasingly standardized treatment strategy. Nevertheless, the persistence of heterogeneity in clinical application highlights the need for further standardization and well-designed prospective studies to consolidate its role in contemporary implant dentistry.

9 | PROPOSED PATHWAY AND CLINICAL RECOMMENDATIONS

Contemporary ZI rehabilitation should be understood as an individualized treatment strategy integrating anatomical conditions, prosthetically driven objectives, functional rehabilitation, and patient-centered considerations within a comprehensive clinical decision-making framework. Based on the available evidence and current clinical concepts discussed throughout this review, clinical recommendations and a proposed clinical pathway for ZI rehabilitation are presented and illustrated (Figure 8). Recommendations (a–d) are supported by relatively consistent clinical evidence and/or consensus agreement, whereas recommendations (e–f) reflect emerging evidence and established clinical principles that, although clinically relevant, remain less directly validated and therefore require greater reliance on expert consensus and clinical judgment.

a. Appropriate case selection remains fundamental for successful ZI rehabilitation, particularly regarding residual bone availability, defect morphology, and the feasibility of graftless reconstruction (Figures 3–5).
b. Preoperative CBCT assessment should be considered mandatory for anatomical evaluation and prosthetically driven planning, while collaboration with ENT specialists may be advisable in selected cases involving sinus pathology (Figures 6E and 7A).
c. Rigid splinting and adequate cross-arch stabilization should be considered fundamental to immediate-loading protocols and favorable biomechanical load distribution (Figure 4D).
d. Long-term success is supported by structured maintenance, adequate hygiene accessibility, soft-tissue stability, and patient compliance, which may help minimize biological and prosthetic complications (Figures 4E,F and 5C,D).
e. Selection of the ZI trajectory should integrate patient-specific anatomy with prosthetically driven objectives, while considering the intended crestal emergence, restorative design, hard- and soft-tissue conditions, and long-term maintainability, rather than adhering to a predefined surgical approach (Figures 1A–C and 2A–D; Table 1).
f. Digital technologies could significantly enhance surgical accuracy, anatomical control, and operative safety in ZI surgery; however, their effective implementation remains dependent on substantial surgical experience and clinical judgment (Figure 7A–C).

10 | CONCLUSION

Despite substantial advances in surgical techniques, prosthetic concepts, and digital integration, the next challenge in ZI rehabilitation

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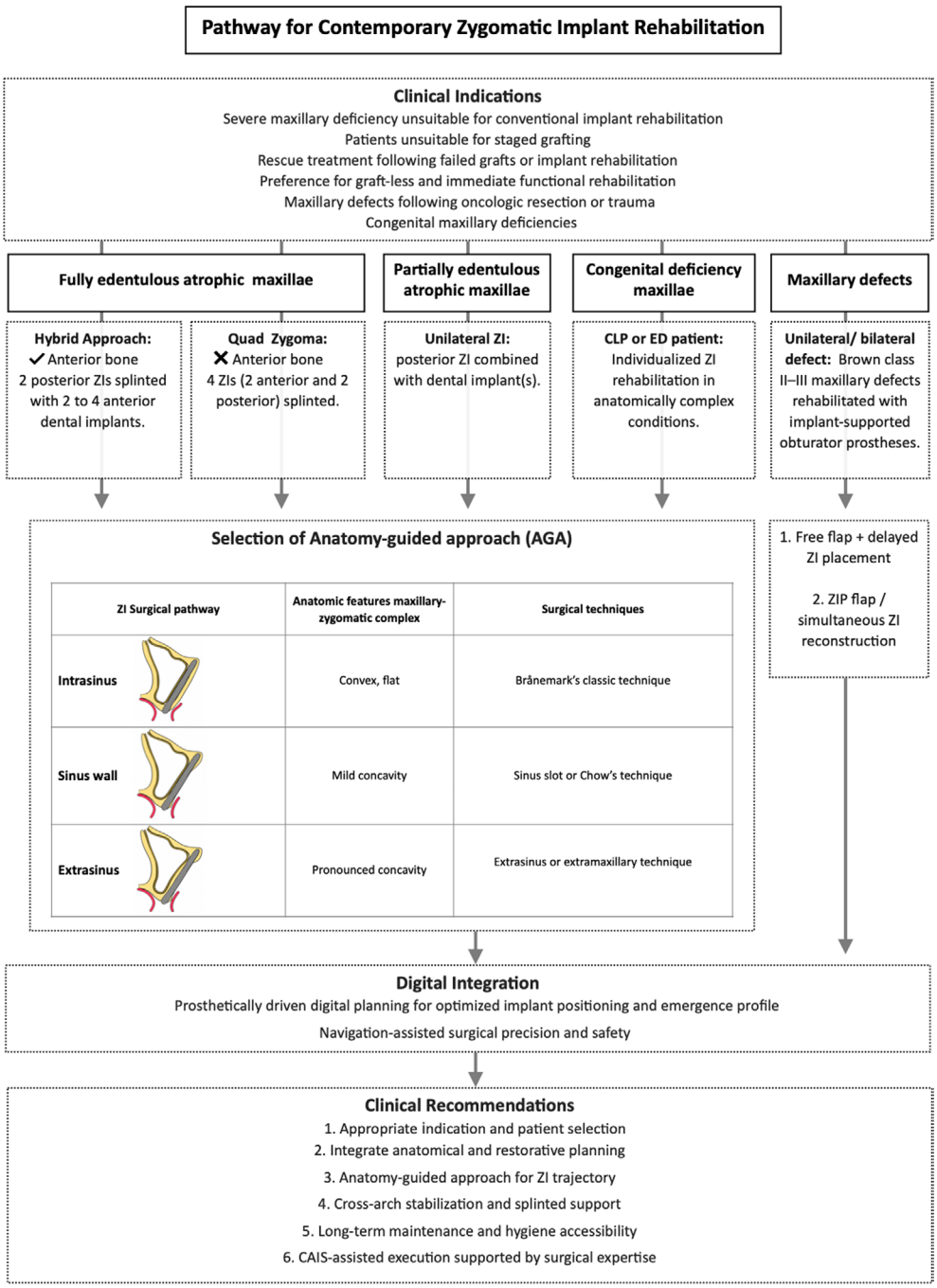


FIGURE 8 Proposed clinical pathway and recommendations for the ZI rehabilitation.

is no longer to demonstrate that the therapy works, but to achieve predictable and reproducible outcomes through appropriate patient selection, treatment planning, surgical execution, long-term maintenance, and integration of digital workflow. Contemporary ZI rehabilitation is no longer limited solely by efficacy, but by the consistent translation of evidence into clinical practice and the resolution of remaining knowledge gaps.

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R. Davó serves as an advisor and speaker for Nobel Biocare. T. Albrektsson serves as a speaker for Nobel Biocare. S. Fan declares no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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