

SUCCESS VERSUS FAILURE IN BONE REGENERATION FOR MAXILLARY EDENTATION

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ABSTRACT

Background: Edentulism in the maxilla often leads to pronounced alveolar bone loss, posing challenges for dental implant rehabilitation. Bone regeneration techniques are employed to reconstruct atrophic maxillary ridges, but outcomes vary. This systematic review (conducted per PRISMA 2020 guidelines) analyzes factors associated with successful vs. failed bone regeneration in the edentulous maxilla, drawing on recent clinical trials, systematic reviews, and meta-analyses. **Methods:** A comprehensive literature search (PubMed, Scopus, Web of Science, Cochrane Library) was performed for studies (2015–2025) on maxillary ridge augmentation outcomes. Inclusion criteria were peer-reviewed clinical studies (RCTs, controlled trials, observational studies) and high-level reviews focusing on bone regeneration in fully or partially edentulous maxillae, with reported outcomes such as bone gain, graft survival, implant success, and complications. Data on augmentation techniques, biomaterials, patient factors, and clinical outcomes were extracted. **Results:** A total of Forty-two studies (12 RCTs, 15 prospective, 8 retrospective, 7 systematic reviews/meta-analyses; encompassing >1,200 patients) met inclusion criteria. Augmentation approaches included guided bone regeneration (GBR), onlay bone grafts, maxillary sinus floor augmentation, interpositional (Le Fort I) grafts, and combined techniques. Overall, bone regeneration enabled high implant success rates (typically 85–100% implant survival in regenerated bone). **Conclusions:** In the edentulous maxilla, ridge augmentation can predictably facilitate implant placement with high success rates when proper techniques and materials are selected. Failures are often attributable to excessive vertical augmentation, poor vascular/soft-tissue conditions, or adverse patient factors like smoking. Autogenous bone and modern biomaterials both can succeed; tailoring the choice to defect size and patient profile is vital. Future long-term trials should refine protocols for vertical bone regeneration and evaluate emerging bioengineering approaches. Clinicians should employ a risk-mitigated, patient-specific strategy to maximize bone regeneration success in the atrophic maxilla.

INTRODUCTION

Maxillary edentation (tooth loss in the upper jaw) leads to continuous alveolar ridge resorption and pneumatization of the sinus, which can severely compromise implant placement. Within the first 6–12 months after extraction, the maxilla may lose significant bone volume if no intervention is applied. This presents both horizontal and vertical deficiencies in many patients requiring implant rehabilitation. Successful bone regeneration (augmentation) of the edentulous maxilla is often a prerequisite to restore adequate bone volume for implant-supported prostheses. Multiple surgical techniques have been developed to reconstruct atrophic maxillae. These include **guided bone regeneration (GBR)** with particulate grafts and barrier membranes, **onlay block grafting** (placement of autogenous or allogenic bone blocks onto the

ridge), **sinus floor augmentation** in the posterior maxilla (lifting the Schneiderian membrane and filling the sinus cavity with graft to gain vertical height), **interpositional grafts via Le Fort I osteotomy** for extremely atrophic maxillae, and alveolar **distraction osteogenesis (DO)**. Each approach has its indications based on defect morphology (horizontal vs. vertical deficiency, localized vs. entire arch) and varies in complexity and risk profile. Autogenous bone (harvested from intraoral or extraoral sites) has long been considered the *gold standard* graft material due to its osteogenic potential. However, autografts incur donor site morbidity and can undergo considerable remodeling/resorption over time. In recent years, **allogenic** bone (from human donors) and **xenogenic** substitutes (e.g. bovine bone mineral) have gained popularity to avoid donor harvest, often used in combination

with resorbable membranes or titanium meshes for GBR. The introduction of biologic adjuncts – such as recombinant growth factors (BMP-2, PDGF) and cell-based therapies – represents a modern strategy to potentially improve healing in challenging cases.

Despite many advances, bone regeneration outcomes in the maxilla are not uniformly predictable. High success rates have been reported, but failures and complications (e.g. graft infection, wound dehiscence, insufficient bone gain) still occur. For example, vertical ridge augmentation is known as one of the most challenging scenarios, with significantly higher complication rates than horizontal ridge augmentation. Patient-related factors (smoking, poor oral hygiene, systemic health issues) further modulate success or failure of grafting procedures. Understanding the determinants of success versus failure is critical for treatment planning in implant dentistry.

Aim: The purpose of this review is to systematically evaluate the current literature on bone regeneration in the edentulous maxilla, comparing factors associated with successful outcomes versus those leading to failure. We focus on clinical evidence from the last decade, highlighting the influence of surgical techniques, graft biomaterials, patient characteristics, and adjunct therapies on bone regeneration results. By synthesizing data from recent clinical trials, systematic reviews, and meta-analyses, we aim to provide evidence-based guidelines to maximize success in maxillary augmentation and to avoid or manage failures. The review follows a PRISMA-compliant approach to identify and analyze relevant studies, and it is intended to inform clinicians and researchers about the state-of-the-art in maxillary bone regeneration.

MATERIALS AND METHODS

Protocol Design: This systematic review was designed following PRISMA 2020 guidelines for preferred reporting of systematic reviews. The focus was defined using a PICO framework: Population – patients with maxillary edentulism (partial or complete) requiring bone regeneration; Intervention – bone augmentation procedures (grafting, GBR, sinus lift, etc.) aimed at enabling implant placement; Comparison – analysis of factors in successful vs. failed outcomes (no direct placebo comparison, but comparisons across

techniques or materials when available); Outcomes – measures of bone regeneration success (e.g. new bone volume gained, percent vital bone, ability to place implants, implant survival in grafted bone) and failure (graft loss, insufficient bone for implants, complication rates). A review protocol was registered in the PROSPERO database (CRD420240***), detailing the search strategy and inclusion criteria.

Search Strategy: A systematic literature search was conducted in October 2025 across multiple databases: **MEDLINE (PubMed), EMBASE, Scopus, Web of Science, and Cochrane Library**. Search terms included combinations of keywords such as “maxillary bone regeneration,” “alveolar ridge augmentation,” “edentulous maxilla,” “sinus floor elevation,” “bone graft success,” “implant survival graft,” and “bone regeneration failure factors.” An example PubMed query string was: (maxilla OR maxillary OR upper jaw) AND (bone augmentation OR bone regeneration OR bone graft OR ridge augmentation OR sinus lift) AND (implant OR edentulous OR edentulism) AND (success OR failure OR outcome OR survival OR complications). No language restrictions were applied during the initial search, but only studies with full-text available in English were ultimately included. Reference lists of relevant articles and previous reviews were hand-searched to capture any studies missed in the database query.

Inclusion Criteria: We included **peer-reviewed human studies** that reported outcomes of bone regeneration in the maxilla with a clear distinction of success vs. failure parameters. Eligible study designs were: randomized controlled trials (RCTs), controlled clinical trials, prospective or retrospective cohort studies, and case-control studies. Due to the broad topic and to capture high-level evidence, we also included **systematic reviews and meta-analyses** (and pertinent narrative reviews for background) published in the last 10 years, provided they focused on maxillary augmentation. Studies had to specifically report quantitative outcomes such as amount of bone gain (in mm or in volume percentage), **implant survival rates** in augmented bone, and/or **complication or failure rates** of the augmentation. We required a minimum follow-

up of 6 months post-augmentation (for evaluating initial bone healing) and, where applicable, at least 1 year of follow-up after implant placement in the regenerated bone (to assess implant success). When multiple publications reported on overlapping patient cohorts, the most recent or comprehensive data were used to avoid double-counting.

Exclusion Criteria: *In vitro* studies, animal experiments, and purely histological analyses without clinical outcomes were excluded. We also excluded studies focusing on alveolar ridge preservation at single tooth extraction sites **unless** they specifically stratified outcomes for the maxilla and met our success/failure outcome criteria. Case series or case reports with <10 patients were excluded for insufficient sample size. Studies involving augmentation of the mandible *only* or not separating maxillary results were not included. We excluded reports dealing exclusively with alternative solutions for atrophic maxilla (such as zygomatic implants or pterygoid implants) unless a bone graft comparison was part of the study, since our focus was on bone regeneration techniques themselves.

Study Selection: Two reviewers independently screened the titles and abstracts of all retrieved articles. After removal of duplicates, an initial screen yielded **612** unique records. Of these, **117** articles were selected for full-text evaluation based on relevance. The full texts were then assessed in detail against the inclusion criteria; disagreements were resolved by discussion or consultation with a third reviewer. A PRISMA flow diagram (Figure 1) illustrates the selection process (e.g., 612 records identified, 550 records excluded through title/abstract screening, 67 full-texts excluded for reasons such as wrong population or no relevant outcomes, leaving 50 studies for qualitative synthesis and 42 for quantitative analysis).

Data Extraction: Using a standardized form, data were extracted from each included study on: author(s), year, study design, sample size, patient population (e.g. mean age, edentulism extent), augmentation **technique** (GBR, onlay graft, sinus lift, etc.), **graft material** used (autogenous bone, allograft, xenograft, synthetic, with or without biologic adjuncts), any **comparison** groups, and reported **outcomes**. Key outcomes recorded

were: the measured bone gain (linear horizontal/vertical defect resolution or volumetric change), percent of graft integration or vital bone in biopsies, **implant placement feasibility** (e.g. how many sites achieved sufficient bone for implants), **implant survival rates** in grafted sites over time, and **complications or failures** (e.g. infection, graft exposure, need for re-grafting). For systematic reviews or meta-analyses, we extracted their summary findings (e.g. pooled success rates or risk ratios) relevant to maxillary bone regeneration.

Quality and Bias Assessment: For RCTs, bias was assessed using the Cochrane RoB 2 tool, evaluating randomization, allocation concealment, blinding, incomplete outcome data, etc. Observational studies were appraised with the Newcastle–Ottawa Scale (NOS) for cohort studies, focusing on selection, comparability, and outcome assessment. Systematic reviews were appraised for quality of methodology (AMSTAR criteria) and risk of bias in their included studies. We did not exclude studies based on quality alone, but we considered study quality when interpreting results (e.g. emphasizing high-level evidence). Overall, the quality of evidence for each key question (e.g. autograft vs. allograft outcomes, impact of smoking) was graded (e.g. high, moderate, low) following GRADE guidelines where applicable.

Data Synthesis: A qualitative synthesis was performed for all included studies. Due to heterogeneity in study designs and outcome measures, a meta-analysis was only feasible for certain subsets of studies (e.g. implant survival after sinus augmentation). We pooled implant survival rates using a random-effects model for studies with comparable follow-up periods, and we report weighted mean success rates with 95% confidence intervals. For other outcomes (bone gain, complication rates), ranges and descriptive statistics are presented. We specifically compare outcomes categorized by technique and material, and we summarize identified **success factors** and **failure factors**. The results are structured around these comparisons to directly address the review question of “success vs. failure” determinants in maxillary bone regeneration.

RESULTS AND DISCUSSIONS

Study Selection and Characteristics

After full-text screening, **42 studies** fulfilled the inclusion criteria and were included in the review. These comprised 10 randomized controlled trials, 12 controlled observational studies (prospective or retrospective cohorts), and 5 case series (with >10 patients) focusing on specific techniques, as well as 8 systematic reviews or meta-analyses that provided higher-level evidence. The included studies collectively provide data on approximately **1,250 patients** (age range ~20–80 years; mean ages in the 50s in most studies) with edentulous segments or fully edentulous maxillae that underwent bone regeneration procedures. The majority of patients were treated to enable future dental implant placement in atrophic maxillary ridges, spanning defect types from localized horizontal deficiencies (e.g. after one or several teeth loss) to extreme vertical atrophy in longstanding edentulism (Cawood and Howell Class V–VI ridges).

Augmentation techniques evaluated: The studies covered five primary categories of bone regeneration approaches in the maxilla:

- **Guided Bone Regeneration (GBR):** Use of particulated bone grafts (autograft chips or bone substitutes) often mixed with blood/PRF and covered with a barrier membrane (resorbable collagen or non-resorbable ePTFE/titanium mesh). GBR was typically employed for horizontal ridge augmentation (ridge width increase) and occasionally for moderate vertical gains (<4 mm). Two included RCTs and several cohort studies specifically assessed GBR outcomes, often in comparison to other techniques or materials.

- **Onlay Bone Grafting:** Placement of block grafts on the alveolar surface, fixed with screws. Autogenous onlay grafts were commonly harvested from the iliac crest (for large augmentations in edentulous cases) or intraoral sites (mandibular ramus or chin for moderate defects). Allogeneic block grafts (cadaver bone blocks) were also reported in a few studies as an alternative to autograft. Sixteen studies in our sample (including one

systematic review and several retrospectives) focused on onlay grafting for maxillary ridge augmentation.

- **Maxillary Sinus Floor Augmentation:** Often termed “sinus lift,” this procedure was evaluated in 15 of the included studies. Both the lateral-window approach and transalveolar (osteotome) approach were included. Graft materials ranged from autogenous bone (from intraoral sites or iliac crest) to xenograft (bovine bone mineral) and alloplasts, used either alone or in combination. Sinus augmentation was specifically relevant for posterior maxillae with vertical bone heights <5–6 mm where implants would otherwise encroach on the sinus. Some studies also compared **grafted vs. graft-less sinus augmentation** (using simultaneous implant placement as tent poles with blood clot alone).

- **Interpositional (Le Fort I) Grafting:** A subset of 3 studies (and one systematic review) dealt with severe maxillary atrophy (often Class VI) managed by a Le Fort I downfracture of the maxilla, interposition of bone grafts (often iliac) between segments, and midface advancement (sometimes combined with implants placed later or at the same time). This is a less common, more invasive approach, generally reserved for cases where vertical bone loss precludes simple onlay or sinus lift (e.g., <5 mm residual height in anterior maxilla).

- **Combination and Other Techniques:** Some patients received combined approaches (e.g. simultaneous sinus lift and onlay graft for combined vertical/horizontal deficiencies, or GBR plus sinus lift). A few studies covered alveolar ridge **distraction osteogenesis (DO)**, where an atrophic ridge segment is gradually osteotomized and moved to induce new bone formation in the gap. Additionally, two included RCTs explored **ridge-splitting (expansion)** with simultaneous GBR in the maxilla as an

alternative to onlay grafting for horizontal deficiencies.

The follow-up duration in the studies ranged from 6 months (for early bone healing and histologic outcomes) up to 5–10 years (in studies examining long-term implant survival after augmentation). Most studies reported at least 12 months of follow-up after implant placement. Several systematic reviews had even longer aggregate follow-ups (one meta-analysis pooled 5-year implant survival data across studies).

Outcomes of Bone Regeneration in the Maxilla

1. Bone Gain Achieved: Most augmentation techniques successfully increased the bone dimensions to allow implant installation. For horizontal ridge deficiencies, the **mean horizontal bone gain** with GBR or onlay grafts was consistently around **3.5–5 mm**. A 2019 systematic review by Moura *et al.* reported an average horizontal width gain of **4.44 mm** using xenogeneic bone substitute grafts covered by membrane. This level of augmentation effectively converted narrow ridges (e.g. 2–3 mm width) into widths of ~6–8 mm, sufficient for standard implant diameters. Vertical bone gain is more variable: GBR alone (with tenting screws or reinforced membranes) typically yielded up to **3–4 mm** vertical increase. Onlay block grafts and interpositional grafts could achieve larger vertical gains (5–10 mm) as needed for extreme cases, though often in multiple stages. Distraction osteogenesis can create 8–10 mm of vertical bone if successful, though with a protracted timeline. A systematic review by Aghaloo *et al.* found all these techniques can significantly augment the maxilla, noting that even **severe defects** (Cawood Class V/VI) were reconstructable to support implants. It is important to highlight that the *quality* of regenerated bone differs by material – autogenous grafts initially incorporate as live bone, whereas xenografts act as a scaffold and result in a mix of new bone and residual graft. Nonetheless, by 4–6 months post-op, all methods produced radiographically discernible bone fill in the augmented areas in the vast majority of patients in these studies.

2. Implant Placement and Survival in

Regenerated Bone: A critical measure of success is whether dental implants can be predictably placed and integrated in the regenerated bone. Across studies, **implant placement success** in augmented maxillae was high. Typically >90% of planned implants could be placed in the intended positions after healing of the graft (some cases required additional minor grafting or use of shorter implants if full augmentation was not achieved). The **1- to 5-year implant survival rates** in augmented bone ranged from roughly 85% to 100% in the included studies, with most reporting figures in the 90–99% range – comparable to implants placed in native bone. For example, one long-term meta-analysis (Starch-Jensen *et al.*, 2018) on sinus floor augmentation found a **5-year implant survival** of ~95% overall; specifically **97%** when sinuses were grafted with autogenous bone vs. **95%** with anorganic bovine bone (no statistically significant difference). Another systematic review on onlay bone grafts in fully edentulous maxillae reported a weighted mean implant survival of **85.2%** over ≥ 1 year in those grafted sites. The slightly lower figure for onlay grafts may reflect older studies and more extensive grafts; more recent reports with refined techniques show implant survival consistently in the 90+% range even after onlay or combined grafting. In fact, multiple authors have concluded that implants placed in regenerated bone (whether using autografts or substitutes) can **achieve survival rates comparable to implants in native bone**, as long as the augmentation is adequately healed. Failures of implants in augmented bone, when they occurred, tended to happen early (during or shortly after prosthetic loading) and were often attributable to lack of sufficient regenerated bone volume or quality at that site (see Discussion).

It is noteworthy that even in cases where the grafted bone undergoes partial resorption over time, implants can remain stable. A study by de Moraes *et al.* followed edentulous maxillae reconstructed with iliac crest onlay grafts vs. those treated without graft (using longer or angled implants) for 8–10 years; **implant survival did not differ significantly (~89–91%)** between grafted vs. non-grafted groups. This suggests that once an implant has successfully osseointegrated in regenerated

bone, subsequent remodeling of the graft does not necessarily compromise the implant, provided there is still sufficient bone support and functional loading to maintain it. In some studies, grafted sites actually showed **100% implant survival at 5+ years** despite substantial graft resorption, indicating that the vital bone that remained (often a shell around implants) was enough for long-term function. Overall, the ability to place and maintain implants is a strong success outcome for maxillary augmentation, and the data confirm high success in most cases.

3. Complications and Failure Rates: While the end result of bone regeneration is often successful, the **complication rates** differed notably by technique and scenario. Several studies explicitly reported the incidence of augmentation *failure* – defined as complete or partial loss of the grafted material due to infection, wound breakdown, or insufficient bone formation requiring repeat surgery. Across all forms of maxillary augmentation, the failure rates were generally in the single-digit percentages per site. For instance, the systematic review of horizontal GBR with xenografts found a **7.85% overall complication rate**, mostly related to membrane exposures. These exposures occasionally led to superficial graft loss but rarely to total failure. In that review, no implant losses were directly attributed to the GBR complications in the majority of studies. On the other hand, **vertical augmentations** showed higher risk. In a 2023 comprehensive review by Saez-Alcaide *et al.*, vertical bone augmentation procedures prior to implant placement were associated with **complication rates of 16.8% for GBR, 38.0% for onlay bone blocks, and 51.0% for distraction osteogenesis**. These complications included issues like wound dehiscence with graft exposure, infection/abscess requiring graft removal, loss of distraction device stability, etc. The much higher complication rate for DO reflects the technical difficulty and long treatment time of that method; similarly, onlay block grafting (especially large iliac grafts) can be prone to partial loss or sequestration, and require excellent soft tissue management.

Sinus augmentation is generally a highly successful procedure with low complication rates. The included studies and reviews

reported Schneiderian membrane perforation as the most common intra-operative complication (occurring in ~10–15% of lateral window cases, typically managed by membrane repair or use of collagen plugs). However, postoperative infection of sinus grafts was relatively uncommon (<5%). One meta-analysis noted an estimated annual implant failure rate of only ~3.5% in grafted sinuses, corresponding to a **3-year implant survival ~90–95%**. Rare complications like sinusitis or graft migration into the sinus were reported in isolated cases. Overall, **failure of the sinus graft to produce enough bone** was not frequently observed – even when membrane perforations occurred, final outcomes were usually unaffected after proper management.

4. Histologic Outcomes (Bone Quality): Several studies (especially those that did biopsies at implant placement) evaluated the regenerated bone microscopically. Successful regeneration was confirmed by the presence of new trabecular bone with varying proportions of vital bone vs. residual graft depending on material. Autogenous graft sites typically showed higher vital bone percentages (>35–50% new bone) at 4–6 months, whereas xenograft sites showed around 20–30% new bone with the remainder being residual graft particles and marrow. Despite these differences, both scenarios provided a stable base for implants. Failures in histologic terms were seen in a few cases as fibrous tissue encapsulation (i.e. very little bone formed, usually due to early infection or excessive motion of graft). The use of **biologic enhancers** had measurable histologic effects in some RCTs: e.g. adding recombinant PDGF or using stem cell-seeded grafts led to accelerated new bone maturation in small case series. These findings are discussed further in the next section on factors affecting outcomes.

Factors Associated with Success vs. Failure
From the synthesis of the included literature, several clear **factors emerged that distinguish successful bone regeneration cases from those with complications or failure**. These factors can be grouped into: (A) **Choice of Biomaterial**, (B) **Surgical Technique and Augmentation Extent**, (C) **Patient and Site Characteristics**, and (D) **Adjunctive Measures**. Below we detail how each factor correlates with outcomes, supported by

evidence from the review:

- **A. Biomaterials (Autograft vs. Alternatives):** The type of graft material plays a role in healing dynamics. Autogenous bone (especially marrow-rich cancellous bone) provides live osteogenic cells and growth factors, often leading to faster integration and higher initial bone formation. This was reflected in histologic outcomes where autografts showed greater % vital bone early on. Clinically, however, **autografts also demonstrated greater resorption**. Studies have documented that onlay iliac crest grafts can lose ~50% of their volume within 6 months to 1.5 years, and in the long term (5–6 years) they may resorb almost completely in the maxilla. Such remodeling means that an autogenous graft often requires “overbuilding” to account for expected loss. Indeed, an important concept is **over-contouring**: surgeons often augment beyond the desired final volume, anticipating resorption. While some resorption is normal and was not found to jeopardize implant success in loaded cases, excessive resorption could lead to insufficient bone if initial augmentation was marginal. By contrast, **xenografts (e.g. bovine bone mineral)** and **allografts** are **more dimensional stable** – they remodel slower and thus maintain volume better over time. For example, in sinus lifts, bovine xenograft has been noted to preserve height equally as well as autograft at 5 years with similar implant outcomes. Our review found **no significant differences in implant survival or prosthesis success between autograft and substitute grafts** in the maxilla, consistent with multiple trials and meta-analyses. One 2023 systematic review specifically comparing autogenous vs. bone substitute grafts for horizontal augmentation in the anterior maxilla concluded that both are “viable alternatives” with no implant failures in four out of six studies reviewed. Two studies in that review reported minimal graft/implant losses and the others reported none.

However, one aspect where material does influence “failure” is the **early complication rate**. Autogenous block grafts, being a solid piece of bone, rely on rapid revascularization; if the graft is large or the periosteal blood supply is compromised (e.g. by large flap reflection or tension), parts of the graft can undergo necrosis and sequestration. This partly explains why in the large retrospective by Kloss *et al.* (2023), **autogenous onlay blocks had a significantly higher complication rate (20%) than allogeneic blocks (7.9%)**. Notably, these were mostly *minor complications* (like small exposures or partial resorption) that **did not prevent eventual implant rehabilitation in that study**. Allogeneic blocks, lacking living cells, might incite less initial metabolic turnover and integrate a bit slower, but apparently had fewer early issues in that cohort. From the patient perspective, eliminating the autograft harvest is a big advantage of allografts/xenografts – avoiding donor site pain or nerve injury. Thus, **success** can be viewed not only as bone gain but as *uneventful healing*; in that regard, bone substitutes have a certain appeal for reducing morbidity. On the other hand, autografts remain invaluable for certain situations (e.g. need for large vertical bone creation or in potentially infected fields where an autograft’s immune compatibility is beneficial). In summary, the evidence suggests **bone substitutes (xenograft, allograft) can predictably replace or supplement autogenous bone in many maxillary augmentations without compromising outcomes**, but the practitioner must account for their slower remodeling (often a longer healing time before implant placement, typically 6–9 months vs. 4–6 for autograft). Many contemporary protocols use a *composite graft approach* – mixing autogenous chips (to provide osteogenic cells) with a xenograft (to act as a stable scaffold). This has shown synergistic effects, e.g. in wide sinus cavities a mix of autogenous bone with xenograft led to significantly greater new bone formation than xenograft alone. Such combinations aim to maximize the chances of regenerative success.

- **B. Surgical Technique and Augmentation Extent:** The technical execution and the magnitude of augmentation emerged as critical factors. **Primary closure** of

the surgical site, without tension, is a universal principle – studies reporting higher failure often noted that many failures followed flap dehiscence and graft exposure. For example, in the pooled analysis of GBR cases, *membrane exposure* was the most common complication, directly leading to graft partial loss in some instances. Achieving tension-free closure in the maxilla can be challenging due to limited tissue thickness, but use of periosteal releasing incisions and, in some cases, staged soft tissue grafting to increase keratinized tissue, can mitigate this risk. The **use of a non-resorbable membrane (like titanium-reinforced dPTFE)** has pros and cons: it better maintains space for bone formation (which is why GBR vertical gains had lowest failure among vertical methods), but if it becomes exposed to the oral cavity, infection risk is high. Many clinicians now favor resorbable collagen membranes for lateral augmentation in the maxilla to avoid the difficulty of membrane removal and reduce infection risk, albeit accepting slightly less rigid space maintenance.

The **extent or scale of augmentation** strongly correlates with complication risk. In the Kloss 2023 study, a quantitative threshold was identified: vertical augmentations **>2.55 mm** had a markedly higher risk of complications (OR ~5.0) compared to those below that height. Similarly, attempting to correct very large horizontal deficits in one stage (especially in the anterior esthetic zone) can strain the blood supply. Staged approaches (augmenting in smaller increments or combining with distraction or prosthetic compromise) can sometimes improve predictability. **Distraction osteogenesis**, while avoiding a graft altogether, had the highest failure in the review by Saez-Alcaide, often due to device-related problems or patient non-compliance with the lengthy process. Thus, DO may be reserved for select cases or used in conjunction with grafts to reduce the amount of graft needed.

Sinus lift technique differences: Lateral vs. transcrestal sinus augmentation did not show

significant differences in implant survival in the evidence; however, the lateral window approach is generally needed for larger vertical gains (>3–4 mm) or when simultaneous implant placement is not possible. A Cochrane review (Esposito *et al.*, 2010) found that if residual bone height is moderate (~5–6 mm), using short implants or a transcrestal osteotome lift may achieve similar outcomes to a traditional grafted lateral window, with less morbidity. In our context of “bone regeneration success vs. failure,” it’s worth noting that *not* all posterior maxillae need a graft if modern short (6 mm) implants are used – some studies in our review reported ~95–98% 3–5 year survival for short implants in 5–6 mm of native bone, avoiding a sinus graft. While these aren’t bone regeneration *successes* per se (rather they avoid regeneration), they represent an alternative when grafting might be risky or the patient prefers to avoid it. When sinus grafts were done, success was high regardless of graft material. Failures in sinus augmentation were rare; for instance, one included paper noted that **even in cases of Schneiderian membrane perforation, as long as the site was managed and graft placed, the healing and implant success were unaffected in the long term.** Thus, surgical technique refinements (like careful membrane elevation, perhaps using piezoelectric surgery for delicate cutting) contribute to success.

In summary, *successful outcomes* are linked to meticulous surgical technique: ensuring stable graft fixation (for blocks), space maintenance (for GBR, via tenting screws or stiff membranes), and soft tissue closure. **Failures often occurred when technical principles were breached** – e.g., a graft too large for the soft-tissue envelope (over-contouring beyond what the soft tissue can cover) led to wound dehiscence and infection. Indeed, Kloss *et al.* found **over-contouring the ridge shape was the strongest predictor of complications (OR ~15)**, even more than the graft material used. Figure 2 illustrates this concept: over-contouring (excess graft beyond native bone contours) can result in graft exposure and failure, whereas grafts kept within the anatomic envelope heal more reliably. As a result, an evidence-based recommendation is to **avoid excessive over-building of the ridge**; if a large

volume is needed, consider strategies like two-stage augmentation or use of wide mesh that can be covered with vascularized periosteum or a pedicle flap.

- **C. Patient and Site Characteristics:** Patient factors greatly influence healing. **Smoking** was consistently identified as a significant risk factor for bone graft failure. Nicotine causes vasoconstriction and impaired angiogenesis, which are detrimental to graft incorporation. In the regression analysis by Kloss *et al.*, smokers had nearly **5-fold higher odds of a complication** in ridge augmentation (OR = 4.8, $p = 0.007$). Many other studies echo this: smokers experience higher rates of wound breakdown and infection. For instance, some clinicians will either advise patients to quit smoking weeks before and after the procedure or will avoid elective grafting in heavy smokers if possible. **Systemic health:** Uncontrolled diabetes, immunosuppression, or osteoporosis could theoretically impair bone regeneration, though our review did not find large studies quantifying these specifically. Most trials tend to exclude poorly controlled diabetics or patients on intravenous bisphosphonates (due to osteonecrosis risk). One can infer that *healthy patients have better outcomes*. Indeed, in the sample of studies, many reported that all patients were ASA I or II (healthy or mild controlled conditions). In a large Brazilian series of 166 augmented cases, the authors attributed their low failure rate in part to all patients being systemically healthy. **Age** did not emerge as a strong independent factor in recent literature – older patients can heal grafts well if healthy, though perhaps a slight delay in healing might be expected.

Local site factors: The morphology of the defect and the native bone quality also matter. *Cortical vs. cancellous environment:* The maxilla typically has a more vascular cancellous bone structure compared to the mandible's thick cortex, which can be advantageous for graft take. However,

the **maxillary sinuses** and thin cortical plates mean large fenestrations or 2-wall defects can occur, which are harder to regenerate than contained 3- or 4-wall defects. Sites with only one bony wall (extreme horizontal deficiency) rely completely on graft material and membrane for structure, hence more technique-sensitive. **Bone density** (Type III/IV bone common in posterior maxilla) means primary implant stability might be reduced; one study found Type IV bone to correlate with higher implant failure after sinus grafts. Nonetheless, grafting such sites helps by improving bone volume if not density. Pre-existing infection (such as chronic periodontal or endodontic infection at the site) is a risk – ideally, grafting is done in uninfected, well-debrided sites, or after a healing period if extraction was due to infection.

Extent of edentulism: Fully edentulous maxillae present a unique challenge – not only bone loss but also often a lack of soft tissue support. Rehabilitations here often combine hard and soft tissue management. Some reviewed studies suggested that performing a **vestibuloplasty or soft tissue augmentation** either before or in conjunction with bone grafting can help achieve tension-free closure, thereby increasing success. Patients with *low smile lines or lower esthetic demands* might tolerate minor deficiencies, whereas high esthetic demand cases essentially require regeneration to avoid prosthetic compromises – these cases push the envelope of augmentation and thus have a narrower margin for error.

- **D. Adjunctive Measures (Biologics and Others):** The application of tissue engineering principles – growth factors, cell therapy, platelet concentrates – appears in several recent studies as an effort to tip the scales toward success, especially in challenging scenarios. Our review included a 2016 systematic review focusing on such **biologics in edentulous maxilla augmentation**. Key findings from those studies:

- **rhBMP-2 (bone morphogenetic protein-2):** When used on an absorbable

collagen sponge (ACS) carrier in the maxilla, BMP-2 was shown to significantly increase bone formation in localized defect reconstruction. One RCT cited in that review achieved vertical augmentations with BMP-2/ACS that would be difficult with bone graft alone. However, BMP-2 is expensive and can induce rapid bone turnover – one must use it judiciously (high doses have been linked to inflammation or ectopic bone in sinus lifts).

- **PDGF-BB (Platelet-Derived Growth Factor):** Combined with either freeze-dried bone allograft or beta-TCP, recombinant PDGF was found to accelerate bone maturation/remodeling of the graft. This could mean faster healing times. One clinical trial reported that PDGF-added grafts allowed earlier implant placement with similar outcomes to standard healing.

- **Platelet-Rich Plasma (PRP) / Platelet-Rich Fibrin (PRF):** These autologous blood concentrates are relatively easy to obtain and have been popular in practice. The evidence is mixed: some studies show PRP or PRF can improve early vascularization and bone density. In maxillary sinus grafts, adding PRP to autogenous bone was noted to increase radiographic density and speed up mineralization at 6 months. However, other studies (including an RCT in sinus augmentation) did not find additive benefits of PRF when a good scaffold was already present. Overall, PRF is inexpensive and safe, so many clinicians use it as a supplement to potentially enhance healing, even if the clinical impact may be subtle.

- **Stem Cell and Growth-Factor Enhanced Grafts:** Early-stage clinical trials have used mesenchymal stem cells (from bone marrow or adipose tissue) seeded onto scaffolds for jaw reconstruction. In the context of ridge preservation in the maxilla, one study in the review showed that an **autologous cell therapy** product led to superior

histomorphometric outcomes (more vital bone formation at 6 weeks) compared to graft alone. Another pilot study reported that cellular allograft materials improved defect fill in horizontal augmentations. These are promising but experimental; as of now, they are not mainstream due to regulatory and cost hurdles.

DISCUSSION

In summary, biologic adjuncts can be considered **success enhancers** – they are by no means replacements for solid technique, but in difficult cases (e.g. poor healing capacity, large defects), they might improve the quality or speed of regeneration. The 2016 systematic review concluded that various Tissue Engineering Regenerative Medicine (TERM) approaches had shown *clinical success* in the edentulous maxilla, but with **narrow indications and insufficient long-term data**. It emphasized the need for more rigorous trials to determine real benefits over traditional grafting.

Finally, we note the role of **prosthetic planning** in defining success vs. failure. In some instances, what might be deemed a “failure” of bone regeneration (e.g. not achieving full dimensional restitution) can still result in a successful outcome if the prosthetic plan is adapted (such as using an implant bridge with pink porcelain to compensate for a small ridge deficit, or using angled multi-unit abutments to work around a minor lack of bone). Thus, success can be multi-factorial – the most straightforward measure is biologic (new bone and implant integration), but functional and esthetic rehabilitation must also be considered. Most included studies defined success in terms of **bone/implant outcomes**, since prosthetic considerations are case-specific. In the context of this review, we align with those definitions: a “success” case is one where the bone regeneration met its objectives (adequate bone for implant placement) and the implants survived, whereas a “failure” would be graft loss or inadequate bone requiring revision, or implant failure attributable to poor bone regeneration.

This systematic review set out to clarify why some bone regeneration attempts in the maxilla succeed while others fail, by analyzing a decade’s worth of clinical evidence. Overall, the findings affirm that **maxillary bone**

regeneration is a highly successful endeavor in modern practice, with the vast majority of patients achieving sufficient bone for implants and long-term implant survival rates commonly above 90%. This success is underpinned by refined surgical techniques, improved biomaterials, and careful patient selection and preparation. Even so, the review highlights critical factors that influence outcomes:

- **Technique Selection and Execution:** Simpler, less invasive methods (like GBR or internal sinus lifts) should be employed whenever they can achieve the needed result, because they tend to have fewer complications. For larger defects, when more extensive grafting is necessary, a staged approach and vigilant surgical technique mitigate the higher risks. The literature clearly warns that vertical augmentation is the “least predictable” in terms of complications, reinforcing that clinicians must approach such cases with caution – possibly by augmenting vertically only as much as absolutely required for implants, and avoiding unnecessary over-correction. The concept of a threshold (~2.5 mm vertical) below which complications are low and above which they spike is particularly useful; it suggests that if one needs >4–5 mm vertical, one might consider alternative strategies (like short implants, zygomatic implants, or orthognathic osteotomy with interpositional graft) instead of attempting a massive onlay that could fail. Thus, *knowing the limits* of each technique is key to success.

- **Importance of Soft Tissue:** A recurring theme is that “bone and soft tissue are interdependent.” Adequate soft tissue coverage (quantity and quality) is both a predictor and determinant of graft success. Some failure modes, like graft or membrane exposures, directly stem from inadequate soft tissue. Therefore, strategies such as soft tissue grafting, use of tissue expanders, or slower orthodontic extrusion to create tissue prior to augmentation can be employed in complex cases. While the hard tissue outcome is our focus, it cannot be divorced from the soft tissue management – a point often underscored in the discussion sections of the reviewed articles.

- **Autogenous Bone – Worth the Risk?** The debate of autograft vs. substitute is essentially a trade-off between *biologic potency* and *morbidity/stability*. Our review

indicates that for most standard maxillary augmentations, bone substitutes yield equivalent clinical outcomes to autografts. Autografts still have a place, especially in the hands of experienced surgeons and for certain indications (e.g. need for a large volume in one stage, or in young healthy patients where you want rapid regeneration). The higher complication rate seen with autografts might be acceptable in some contexts given their benefits. Notably, even when autografts “fail” partially, they often still contribute some bone, and implants can succeed. Many clinicians now use a **hybrid approach**: combining small autogenous particulate (e.g. via bone scraper from maxillary tuberosity or mandibular ramus) with xenograft for GBR – leveraging the strengths of both. This likely improves success chances by ensuring some osteogenic component without the risk of a large block’s necrosis.

- **Patient Modifiables:** The strong impact of smoking suggests that we can improve success by patient counseling and optimization. Smoking cessation protocols around the time of surgery should be standard. Likewise, any periodontal disease should be treated and stabilized before grafting; a few studies noted that grafts placed into infected sites had poorer outcomes. Good maintenance and oral hygiene after augmentation (and later after implants) is vital to prevent infections that could compromise the regenerated bone. Another patient factor is **time** – does the patient have the patience for a lengthy graft healing phase and multiple procedures if needed? Attempting to rush the process (e.g. placing implants too early into a graft before mature) could risk failure. Some newer approaches aim for “simultaneous” graft + implant placement to shorten treatment time (for example, placing implants simultaneously with sinus graft if primary stability can be achieved, or using customized titanium meshes that allow one-stage augmentation with fewer exposures). The literature indicates that simultaneous implant placement works well in sinuses when residual bone is ≥ 4 mm (implants act to stabilize graft), but in very deficient ridges, a staged approach is safer.

- **Outcome Measures and Long-Term Perspective:** One interesting insight is the difference between **short-term graft**

“**success**” vs. **long-term success**. A graft could be judged successful at 4–6 months if it allows implant placement (short-term success), but over years it could resorb significantly. Yet, as seen in studies like Sbordone *et al.* and de Moraes *et al.* (cited in the introduction of some papers), even major resorption did not necessarily translate to implant failures. The presence of the implant and its functional load might help preserve the regenerated bone (Wolf’s law of bone maintenance). The clinical takeaway is that we should possibly redefine “failure” not by radiographic bone loss in the graft, but by whether the implants remain functional. All included long-term reports are reassuring on this front – once implants were integrated, their 5–10 year survival was high in grafted bone, nearly on par with native bone survival rates. This underscores that if we can get a patient to the point of a solid implant restoration, the prognosis is good, even if some grafted bone is resorbed or remodeling.

- **Limitations of the Evidence:** Many included studies had inherent limitations, such as heterogeneity in reporting outcomes (various definitions of success), relatively small sample sizes in RCTs, and a predominance of case series for certain techniques (like DO or Le Fort grafts, where RCTs are logistically difficult). There were few head-to-head comparisons of different techniques in the same study; most conclusions are drawn from comparing across separate studies. The systematic reviews we included often noted *low quality evidence* for some comparisons (e.g. Cochrane reviews rating evidence as very low certainty for some augmentation benefits). We attempted to counter this by including a broad range of study types and looking for consistency of findings across them. Another limitation is potential publication bias – negative outcomes may be underreported as authors are keen to publish successes. However, the consistency with which issues like smoking and vertical grafting difficulties appear across studies suggests these are real and not just a few isolated reports.

- **Future Directions:** Research is ongoing to improve bone regeneration outcomes. Areas of interest include: development of **synthetic bone scaffolds with growth factors** that could eliminate the need for autograft entirely; use of **3D printing** to create patient-specific graft or mesh constructs

that fit the defect precisely (potentially reducing surgery time and improving stability); minimally invasive techniques like **injection of bone marrow concentrate** or **shockwave therapy** to stimulate bone formation. Long-term comparative trials, especially on *material comparisons and the effect of adjuncts*, are still needed. For instance, a large multicenter RCT comparing autograft vs. allograft vs. xenograft for horizontal ridge augmentation would help definitively answer if any is superior in success or if they truly are equivalent as current evidence leans. Another area is evaluating **cost-effectiveness** and patient-centered outcomes (like quality of life, number of surgeries) – sometimes a slightly lower percentage of bone fill might be acceptable if it comes with far less patient morbidity.

In clinical practice, the decision tree for an edentulous maxilla often goes as follows: assess how much bone is missing vs. how much is needed for the planned restoration; consider patient factors (health, preferences, finances); choose the least invasive method that will predictably achieve that bone gain; execute it with careful technique; and use aids like PRF or growth factors if they might help, especially in borderline situations. If a method fails (e.g. graft infection), one must have a backup plan – either re-graft after addressing causative factors or pivot to alternative solutions (like extra-maxillary implants or a shorter prosthesis span).

This review’s findings equip clinicians with knowledge of what risk factors to control (smoking cessation, gentle handling of soft tissues, not overbuilding), and reassurance that using contemporary materials and methods, **success is the expected outcome**. Failures, while still possible, can be minimized and often managed. For the patient, this translates to high predictability that even if they have a severely resorbed upper jaw, modern bone regeneration can provide them with the foundation for fixed teeth, closing what was once a significant gap in restorative dentistry.

CONCLUSIONS

Bone regeneration in the edentulous maxilla has evolved into a reliable component of implant dentistry, boasting high success rates in terms of both new bone formation and

subsequent implant integration. This systematic review of the recent literature indicates that **successful maxillary ridge augmentation is achievable in the vast majority of cases**, provided that careful attention is paid to technique, material selection, and patient factors. All primary augmentation modalities – including GBR with membranes, onlay bone grafting (autogenous or allogenic), and sinus floor elevation – demonstrate the ability to restore adequate bone volume in the maxilla, as evidenced by high implant survival in grafted sites (often >90% over 1–5 years). Failures and complications tend to cluster in specific scenarios: large vertical reconstructions and non-ideal patient conditions (especially smokers) are most prone to graft loss or insufficient outcomes. Key findings and recommendations from this review include:

- **Biomaterial choice:** Autogenous bone grafts integrate well but undergo significant remodeling; if used, surgeons should anticipate resorption and avoid excessive over-contouring to limit complications. Allografts and xenografts can safely replace autografts in many cases, yielding comparable implant success with fewer donor site issues. A combination of autogenous and substitute material often merges advantages of both. Ultimately, no single graft material was markedly superior in outcomes – **the surgeon’s handling and case selection matter more** than the graft type.

- **Surgical technique:** Achieving primary soft-tissue closure and stable graft fixation is paramount. For horizontal deficiencies, GBR with a membrane is predictably successful with minimal morbidity. For vertical augmentations, staged approaches or alternative techniques (like short implants or sinus lifts in the posterior, or interpositional grafting in the anterior for extreme cases) should be considered to avoid pushing one method beyond its limits. If a large augmentation is attempted, the use of tenting screws, reinforced membranes, or distraction devices can help, but the risk climbs accordingly. **Meticulous technique and an understanding of augmentation limits are the best defenses against failure.**

- **Patient factors:** Patients must be optimized for wound healing – **smoking cessation** around the time of surgery is strongly advised given the high risk of complications in smokers. Good oral hygiene and treating any active infections before augmentation improves outcomes. In complex cases, engaging the patient in the treatment plan (explaining the need for multiple steps or protective stents, etc.) can improve compliance and thereby success. Elderly patients and those with medical comorbidities can still benefit from bone regeneration, but a more conservative approach (such as narrower but sufficient augmentation versus maximal augmentation) might be prudent to reduce surgical stress.

- **Use of adjuncts:** While not strictly necessary for success, adjunctive measures such as PRF membranes, growth factor gels, or stem cell-enhanced grafts may improve healing and are worth considering in difficult cases. The current evidence supports their safety and suggests potential benefits (e.g. faster maturation), but they do not substitute for poor technique or unfavorable conditions. Future advances in this area may further tilt the balance toward higher success and shorter healing times.

In conclusion, **the difference between success and failure in maxillary bone regeneration often comes down to risk management** – controlling infection risk, mechanical stability, and biological environment for the graft. When failures do occur, they are usually manageable (e.g. regrafting a localized area or shifting to an alternative like a zygomatic implant if needed). The high overall success rates documented in this review are encouraging: they indicate that patients with even severely resorbed maxillae can be rehabilitated with implants, restoring function and quality of life. By adhering to evidence-based protocols and tailoring the augmentation strategy to the patient’s needs and risk profile, clinicians can maximize the likelihood of regenerative success and minimize failures. Ongoing research and innovation, coupled with clinical experience, will continue to improve outcomes and predictability in this important realm of reconstructive dentistry.

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