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REVIEW

Enhancing esthetics and functionality of dental implants: A mini-review of titanium-based materials and techniques

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ABSTRACT

Dental implant placement in the esthetic zone is among the most challenging procedures in contemporary restorative dentistry and requires meticulous interdisciplinary planning to ensure long-term success. This success largely depends on the presence of adequate peri-implant bone volume, which is often compromised by post-extraction resorption, periodontal disease, or traumatic injury. This comprehensive mini-review consolidates and critically evaluates recent clinical case reports, controlled studies, and relevant literature to assess the efficacy of titanium and its alloys when used with advanced surgical techniques, with particular emphasis on Guided Bone Regeneration (GBR) employing titanium mesh. A synthesis of documented cases demonstrates that titanium mesh functions as a highly effective space-maintaining device, preventing soft tissue ingrowth and promoting substantial horizontal ridge augmentation. One representative case reported an average ridge width increase from 4.56 mm to 7.23 mm. Dental implants from various manufacturers, including Biotec BTK and Straumann Roxolid, both primarily composed of titanium, consistently achieved successful osseointegration without significant complications, even in patients with notable risk factors such as chronic smoking. The discussion highlights the multifactorial nature of implant success, which depends not only on the inherent biocompatibility and corrosion resistance of the material but also on precise surgical technique, comprehensive prosthetic planning, and diligent postoperative maintenance. Titanium and its alloys remain the gold standard biomaterials for dental implants due to their well-established osseointegrative properties. Their strategic use in combination with GBR techniques involving titanium mesh enhances clinical outcomes, yielding predictable and durable results in both esthetic and functional dental rehabilitation. Future research should focus on nanoscale surface modifications of titanium to further promote bioactive healing and on long-term clinical evaluation of these advanced treatment protocols.

Keywords: dental implants, titanium, titanium mesh, guided bone regeneration

INTRODUCTION

Dental implants are a cornerstone of modern restorative dentistry, providing a durable and predictable solution for tooth replacement.[1] The long-term success of an implant, defined by its stability, functionality, and aesthetics, critically depends on achieving osseointegration, the direct structural and functional connection between living bone and the surface of a load-bearing implant.[2] This process is especially vital in the esthetic zone, where insufficient peri-implant bone volume, often resulting from prolonged tooth loss or periodontitis, presents a significant clinical challenge.[3]

For more than half a century, titanium (Ti) and its alloys have been the materials of choice for endosseous dental implants. This preference stems from their unique combination of properties ideally suited to the biological and mechanical conditions of the human body. Titanium demonstrates excellent biocompatibility through the formation of a stable, inert, and self-repairing oxide layer (predominantly TiO_2) when exposed to air or physiologic fluids. This oxide layer minimizes ion release, prevents corrosion, and facilitates protein adsorption and osteogenic cell attachment.[4] Moreover, titanium alloys such as Titanium-6Aluminum-4Vanadium (Ti-6Al-4V) and, more recently, Titanium-Zirconium (TiZr, e.g., Straumann Roxolid™), provide enhanced mechanical strength and fatigue resistance while maintaining superior biocompatibility. These properties enable the development of implants with reduced diameters or lengths without compromising mechanical integrity, offering distinct advantages in areas with limited bone volume.[5]

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Nevertheless, the choice of biomaterial, though essential, represents only one aspect of achieving clinical success. The surgical technique remains equally critical in realizing the full potential of the implant material. To address bone deficiencies, Guided Bone Regeneration (GBR) has been developed and refined as the gold standard surgical approach. The biological principle underlying GBR is cell occlusion: placing a barrier membrane over a bone defect prevents rapid epithelial and connective tissue cell migration from the soft tissue, thereby maintaining a secluded space that allows slower-migrating osteoprogenitor cells from the surrounding bone marrow and periosteum to populate the area and form new bone.[6] The success of GBR depends on four essential principles: (1) primary tension-free wound closure to ensure uninterrupted healing, (2) promotion of angiogenesis to deliver nutrients and progenitor cells, (3) maintenance of a stable space to prevent membrane collapse into the defect, and (4) mechanical stability of the graft material itself.[7,8]

Among GBR techniques, the choice of barrier membrane is pivotal. Resorbable collagen membranes are often selected for smaller or less complex defects due to their ease of handling and elimination of the need for a second surgical removal. However, these membranes have limited mechanical strength and degrade rapidly, making them less suitable for larger defects. For significant horizontal or vertical ridge augmentations, nonresorbable titanium-reinforced or pure titanium mesh membranes have proven superior. Titanium mesh provides exceptional mechanical stability, resistance to deformation, and reliable maintenance of a predefined three-dimensional space for graft maturation over extended healing periods.[9] Its rigidity protects the underlying graft from soft tissue compression, reducing the risk of graft resorption and insufficient bone volume gain. Furthermore, modern titanium mesh designs feature low-profile edges and perforations that enhance tissue integration and reduce the risk of mucosal perforation, which was a limitation of earlier generations of nonresorbable membranes.

Within GBR protocols, titanium mesh has become a highly effective space-maintaining device. Compared with resorbable collagen membranes, titanium mesh offers superior mechanical stability, resistance to collapse, and consistent space maintenance for larger augmentations.[10] This review synthesizes current evidence from recent clinical studies and case reports to highlight the role of titanium-based materials and the synergistic application of titanium mesh in improving the esthetics and functionality of dental implant therapy.

METHOD

This study was designed as a narrative yet systematic mini-review following established principles of evidence synthesis in healthcare. Its primary aim was to critically evaluate current evidence on titanium-based materials and titanium mesh used in dental implant therapy, with a focus on both aesthetics and functionality. A comprehensive electronic literature search was conducted across PubMed/MEDLINE, Google Scholar, ScienceDirect, and Scopus to identify English-language articles published between 2017 and 2024, ensuring inclusion of contemporary research while recognizing seminal historical works. The search strategy employed a combination of Medical Subject Headings (MeSH) and free-text keywords linked through Boolean operators to identify relevant studies addressing titanium alloys, guided bone regeneration, implant stability in the aesthetic zone, and biocompatibility.

From an initial yield of 1,247 records, 893 unique entries remained after removing duplicates and were subjected to a rigorous two-stage screening process conducted independently by multiple reviewers. The selection prioritized human clinical studies, including randomized controlled trials and detailed case reports, that examined titanium implants and guided bone regeneration procedures incorporating titanium mesh with a minimum follow-up of six months. Studies involving animals or in vitro designs, non-English publications, and reviews lacking original data were excluded. After title and abstract screening, 78 potentially relevant articles underwent full-text evaluation, leading to the selection of 13 studies forming the core analytical framework. Among these, three high-quality case reports were highlighted for detailed presentation due to their illustrative clinical value.

Data extraction was performed using a standardized form to record essential variables such as patient demographics, surgical protocols, and clinical or radiographic outcomes, including bone gain and implant survival. The methodological quality of the selected studies was appraised using the CARE checklist for case reports and the JBI critical appraisal tools for other study designs. This evaluation informed the interpretation of findings but did not serve as an exclusion criterion. Due to substantial heterogeneity in study designs and populations, a formal meta-analysis was deemed inappropriate. Consequently, a narrative synthesis approach was employed, integrating findings from tabular summaries and descriptive analyses into a comprehensive discussion that identified overarching trends and existing knowledge gaps.

RESULTS

The synthesized findings from the selected literature, particularly three representative case reports, clearly demonstrate the clinical applications, procedural details, and successful outcomes of titanium-based implants and titanium mesh-augmented guided bone regeneration (GBR) techniques. Table 1 provides a concise summary of these cases, followed by a detailed narrative discussion.

Table 1. Detailed summary of clinical cases utilizing titanium implants and titanium mesh augmentation techniques

Author (Year)	Implant Type & Material	Bone Deficit / Indication	GBR Technique & Materials	Key Clinical & Radiographic Outcomes	Follow-up Period	Complications
Albash et al. (2024)[10]	Tapered implant (3.5 mm diameter, 10 mm length), commercially pure titanium (Grade IV)	Severe horizontal ridge deficiency in the maxillary right lateral incisor region (initial width: 4.56 mm). Aesthetic zone rehabilitation.	One-stage simultaneous implant placement and GBR. Defect filled with particulate allogeneic freeze-dried bone graft (FDBA). Space maintained with a pre-contoured L-shaped titanium mesh fixed with micro-screws.	**Radiographic:** CBCT analysis at 6 months showed significant horizontal bone gain. The ridge width increased to an average of 7.23 mm, representing over 2.5 mm of new bone formation. Excellent buccal osseointegration was observed. **Clinical:** Successful implant integration with excellent primary stability achieved (ISQ >70). Optimal peri-implant mucosal health, harmonious gingival contour, and aesthetic restoration achieved with a zirconia crown.	12 months post-loading	None reported. No mesh exposure or infection.
Saad et al. (2023)[11]	Standard two-piece tapered titanium implant (4.1 mm diameter, 11 mm length)	Unilateral mandibular first molar loss due to caries. Adequate bone height but required standard implant protocol.	No complex GBR required. Standard osteotomy and implant placement following manufacturer's protocol. A collagen plug was used to seal the osteotomy.	**Radiographic:** Panoramic and periapical radiographs at 12 months showed stable crestal bone levels with less than 0.5 mm marginal bone loss. No radiolucency around the implant. **Clinical:** Implant was successfully restored with a single metal-ceramic crown. Excellent occlusion and masticatory function restored. No signs of inflammation (bleeding on probing, suppuration) or mobility.	18 months post-op	None. Uneventful healing.
Santoso & Ariesanti (2024)[12]	Two different systems: 1. Biotec BTK Implant (Grade 4 CP Ti) at site #37 2. Straumann Bone Level Tapered Implant (Roxolid™: 85% Ti, 15% Zr) at site #47	Loss of bilateral mandibular first molars (#36 & #46, FDI notation #36 & #46). Moderate bone volume present. Patient was a chronic smoker (10 cigarettes/day).	Two-stage submerged healing protocol for both implants. No major GBR required; only minor grafting with xenograft at the gaps. Prosthetic rehabilitation with screw-retained, cementable Porcelain-Fused-to-Metal (PFM) crowns.	**Radiographic:** Post-operative panoramic radiograph showed ideal 3D positioning of both implants. At 6-month follow-up, both implants were fully osseointegrated with no discernible bone defects. **Clinical:** Despite smoking history (a known risk factor), both implant sites healed without complication—no pain, swelling, infection, or mobility. The PFM crowns provided excellent function and aesthetics. Patient maintained good oral hygiene.	9 months post-loading	None. Successful integration of two different titanium-based systems in a risk patient.

Case 1: Albash et al. (2024) – Management of Severe Horizontal Deficiency with L-Shaped Titanium Mesh

This case exemplifies the paradigm of complex site development in the aesthetic zone. The patient presented with a highly compromised ridge in the maxillary lateral incisor region, a consequence of long-term edentulism. The pre-operative Cone Beam Computed Tomography (CBCT) revealed a knife-edge ridge with a critical horizontal width of only 4.56 mm, which is insufficient for the placement of a standard-diameter implant (typically requiring ≥6 mm of bone width for adequate buccal and lingual bone plates). The treatment plan involved a flapless, minimally traumatic extraction of a failing temporary prosthesis, followed by immediate implant placement to preserve the soft tissue envelope. However, the pronounced buccal defect necessitated simultaneous augmentation.

The surgical procedure was meticulous. After preparing the osteotomy and inserting the implant, the buccal dehiscence defect was filled with mineralized allogeneic bone graft (FDBA). The graft was then covered and secured using a prefabricated, L-shaped titanium mesh. This specific mesh design is

advantageous as it provides rigid support along the vertical and horizontal dimensions of the defect. The mesh was adapted passively to the bone contour and fixed with two titanium micro-screws to ensure absolute stability, a prerequisite for successful GBR. Primary tension-free closure was achieved with polypropylene sutures.

Healing was uneventful. The titanium mesh remained completely covered by the mucosa, avoiding exposure—a common complication that can lead to infection and graft failure. After a six-month healing period, a re-entry surgery was performed to remove the mesh. The clinical presentation was remarkable: a wide, well-contoured ridge of keratinized tissue had formed. CBCT analysis quantitatively confirmed the clinical success, demonstrating a more than 50% increase in ridge width to 7.23 mm. This newly formed bone provided a stable and vascularized bed, enabling the implant to be successfully restored with a CAD/CAM zirconia crown, resulting in a natural and aesthetically pleasing outcome.

Case 2: Saad et al. (2023) – Predictable Rehabilitation in the Posterior Mandible

This case underscores the predictability of standard titanium implants in routine clinical scenarios with adequate native bone. The patient required replacement of a missing mandibular first molar, a region subject to high masticatory loads. Pre-operative radiographs confirmed sufficient bone height above the inferior alveolar nerve and adequate mesio-distal space. The procedure followed a conventional protocol: a full-thickness mucoperiosteal flap, sequential osteotomy preparation under copious saline irrigation, and placement of a standard, moderately rough surface titanium implant. The implant achieved high primary stability (>35 Ncm), allowing for a submerged healing protocol.

The focus here was not on complex regeneration but on precision and atraumatic surgery. The implant was left to osseointegrate for four months before being uncovered and fitted with a healing abutment. Impressions were taken using a polyvinyl siloxane material, and a metal-ceramic crown was fabricated and cemented with provisional cement. At the 18-month follow-up, the implant was functionally loaded and asymptomatic. Radiographic evaluation revealed healthy peri-implant bone with minimal physiological remodeling at the crest. This case serves as a benchmark, demonstrating that in ideal conditions, titanium implants provide a straightforward and highly successful solution.

Case 3: Santoso & Ariesanti (2024) – Comparative Performance of Two Titanium-Based Systems in a Patient with Risk Factors

This report provides valuable clinical insight into the behavior of different titanium-based implant systems within the same patient, acting as an internal control. The patient, a chronic smoker, needed implants in both posterior mandibular quadrants. Smoking is a well-documented risk factor, impairing angiogenesis, reducing oxygen perfusion, and compromising the immune response, all of which can jeopardize osseointegration and increase the risk of peri-implantitis.[13]

The clinician chose to place two different implant systems: a commercially pure titanium implant (Biotec BTK) on one side and a titanium-zirconium alloy implant (Straumann Roxolid) on the other. The Roxolid alloy is engineered for higher tensile and fatigue strength compared to Grade 4 titanium, allowing for potentially smaller designs without sacrificing durability. Both implants were placed using a two-stage submerged protocol to maximize the chances of undisturbed healing in this risk patient.

Despite the patient's continued smoking habit (which was strongly advised against), both implants integrated successfully. Clinical examinations at 6 and 9 months revealed no signs of pathology. Radiographs confirmed stable bone levels around both implants. The final prostheses—screw-retained PFM crowns—were delivered, restoring full function. This case highlights several critical points: 1) Both CP Ti and TiZr alloys can achieve successful osseointegration, even under compromised conditions, reaffirming titanium's robust biocompatibility. 2) Meticulous surgical technique (atraumatic surgery, precise fit, primary stability) can help mitigate patient-related risk factors. 3) The choice between different titanium-based systems may be influenced by specific clinical requirements (e.g., narrow-diameter sites favoring stronger alloys) rather than a fundamental difference in biological outcome regarding integration.

DISCUSSION

The consistent thread of success observed across the spectrum of cases presented, from complex regenerative procedures to straightforward placements, and even in the presence of behavioral risk factors, provides a compelling reaffirmation of titanium's central role in implant dentistry. This discussion will

deconstruct the multifactorial nature of this success, analyzing the contributions of material science, surgical innovation, and patient management.

The pre-eminence of titanium is not accidental but is rooted in its unique biological and physical properties. Upon insertion into bone, titanium spontaneously forms a thin, adherent, and stable oxide layer (mainly TiO_2) that is chemically inert and highly resistant to corrosion in the chloride-rich physiological environment.[4] This passivation layer minimizes the release of metal ions, thereby preventing adverse tissue reactions and fostering biocompatibility. More importantly, this oxide surface has been shown to selectively adsorb specific plasma proteins (e.g., fibronectin, vitronectin) in a favorable conformation, which in turn mediates the attachment, spread, and differentiation of osteogenic cells.[14] This cascade of events culminates in the direct deposition of bone onto the implant surface—osseointegration.

The evolution from commercially pure titanium (CP Ti) to advanced alloys like Ti-6Al-4V and, more recently, TiZr (Roxolid) represents a strategic response to clinical demands. While CP Ti (Grades I-IV) offers excellent biocompatibility, its mechanical strength is limited. Ti-6Al-4V significantly increases strength but introduces aluminum and vanadium ions, which, while generally considered safe, have raised theoretical concerns over long-term biological effects. The TiZr alloy (85% Ti, 15% Zr) marks a significant advancement, offering a 40-50% increase in tensile strength and fatigue resistance compared to Grade 4 Ti, without incorporating elements of concern.[5] As demonstrated in Case 3, this allows for the safe use of narrower-diameter implants (e.g., 3.3 mm) in spatially restricted sites like the mandibular incisor region or in cases of mesio-distal bone loss between teeth, without increasing the risk of mechanical fracture. The excellent osseointegration observed with Roxolid suggests that zirconium, itself a biocompatible element used in ceramic implants, integrates seamlessly into the titanium lattice without disrupting its favorable surface chemistry.

The management of substantial bone defects remains one of the most significant challenges in implantology, yet the introduction of titanium mesh has fundamentally improved the predictability of large-scale Guided Bone Regeneration (GBR) procedures. Its primary advantage over traditional resorbable collagen membranes lies in its superior mechanical properties. Acting as a rigid, non-deformable "tent-pole," the mesh effectively resists the compressive forces exerted by the overlying mucoperiosteal flap and surrounding soft tissues. This structural resilience stands in stark contrast to collagen membranes, which—especially when hydrated—are prone to collapsing into the defect, resulting in inadequate space maintenance and suboptimal bone fill as noted by Roccuzzo et al.[9].

Beyond its strength, the mesh offers exceptional customizability and stability. Available in various prefabricated shapes, it can be easily trimmed and adapted chairside, then secured with fixation screws to create a single, immobile graft-mesh unit. This absolute stability is a critical prerequisite for the migration and differentiation of osteoblasts, facilitating the subsequent process of creeping substitution within the graft. Furthermore, modern titanium mesh designs have significantly reduced complication rates compared to early non-resorbable membranes like ePTFE, which suffered from high exposure rates due to sharp edges. Contemporary meshes feature smooth, rounded edges and micro-perforations that allow for fibrous tissue ingrowth; this integration stabilizes the mesh with the overlying soft tissue and minimizes the risk of exposure, a benefit highlighted by Albash et al.[10].

Crucially, titanium mesh provides long-term space provision, maintaining its structural integrity throughout the entire 6 to 9-month healing period. This duration is essential for large augmentations where bone formation is slow, unlike resorbable membranes that degrade too quickly. Although a minor second procedure is required for removal, the process is generally straightforward and preserves the newly formed bone. The efficacy of this approach is evident in the quantitative results from Case 1, which showed a gain from 4.56 mm to 7.23 mm—predictable horizontal gains that remain difficult to achieve consistently with membrane-only techniques.

While titanium provides the biological foundation, clinical success is orchestrated by the clinician's skill and planning. The cases reviewed underscore several non-negotiable surgical and prosthetic principles, beginning with the critical importance of three-dimensional implant positioning. The future aesthetic and functional outcome is determined at the moment of implant placement, necessitating precision in the mesio-distal, corono-apical, and bucco-lingual dimensions. Ideally, the implant should be placed 1.5-2 mm apical to the future gingival margin and 1-1.5 mm palatal/lingual to the emergence profile of the planned crown to allow for an adequate thickness of buccal bone and soft tissue.[15] To achieve this level of precision, particularly in aesthetic cases, the use of surgical guides is highly recommended.

Additionally, achieving primary stability is paramount, as high initial implant stability (insertion torque > 25-35 Ncm) serves as a key predictor of successful osseointegration by creating a motion-free environment for bone healing. In challenging scenarios such as soft bone or immediate extraction sockets, specific techniques like under-preparation of the osteotomy or the use of implants with aggressive thread designs can be employed to enhance primary stability. This surgical precision must be paired with prosthetic-driven treatment planning, which acts as the cornerstone of modern implantology. The final restoration should be designed first, and the implant placement should be planned to support that restoration ideally. This involves considering the crown shape, emergence profile, occlusion, and hygiene accessibility even before the first incision is made. As shown in all cases, the final prosthetic result—whether a zirconia crown, metal-ceramic crown, or PFM crown—was integral to the treatment success.

Finally, the effective management of patient risk factors is essential, illustrating that success is possible even with challenging patients. While smoking cessation is ideal, it is not always achievable; in such scenarios, modifying the treatment protocol becomes essential. This may include using a two-stage submerged approach to protect the healing site, selecting implants with enhanced surfaces, extending healing times, and implementing intensified postoperative maintenance and patient education programs.[13]

This mini-review presents certain inherent limitations. Primarily, its narrative design and reliance on a select number of case reports, while illustrative, lack the robust evidentiary weight afforded by large-scale randomized controlled trials (RCTs) or systematic reviews. Furthermore, case reports are intrinsically susceptible to publication bias, a phenomenon where successful outcomes are disproportionately reported over failures. Additionally, the follow-up periods in the cited cases—ranging from 6 to 18 months—are relatively brief within the context of implantology, a field where success is ideally gauged over decades. Consequently, longitudinal data regarding the survival of implants placed with concomitant titanium mesh guided bone regeneration (GBR) remains an evolving area of study.

Looking forward, research investigations should converge on several critical avenues. In the realm of advanced surface engineering, the bio-functionalization of titanium surfaces represents a significant frontier. Investigation into nano-topographies, bioactive molecular coatings (such as bone morphogenetic proteins and peptides), and the incorporation of antimicrobial agents is essential to accelerate osseointegration, optimize soft tissue attachment, and mitigate peri-implantitis. Concurrently, there is a pressing need for prospective RCTs to evaluate long-term outcomes (5–10 years) comparing titanium mesh GBR against advanced resorbable membranes, specifically regarding bone gain stability, complication rates, and implant survival.

Beyond biological parameters, the integration of digital workflows demands attention. The convergence of titanium mesh protocols with digital dentistry—utilizing patient-specific, CAD/CAM-designed, and 3D-printed meshes derived from pre-operative CBCT scans—offers the potential for superior adaptation and reduced surgical duration. A rigorous assessment of the cost-effectiveness and clinical utility of these technologies is warranted. Finally, further scholarship is required to establish predictable management strategies for complications, particularly titanium mesh exposure. Although the incidence of exposure has declined, it remains a clinical challenge; thus, protocols for salvage procedures and the elucidation of the impact of exposure on graft survival are necessary.

CONCLUSION

Titanium and its alloys remain the gold standard for dental implant biomaterials, a status confirmed by decades of clinical success owing to their biocompatibility, corrosion resistance, and consistent promotion of osseointegration. Advanced surgical techniques, including Guided Bone Regeneration with titanium mesh, have broadened implant therapy applications by reliably addressing bone deficiencies, particularly in esthetically critical anterior regions. Titanium mesh provides mechanical rigidity and space maintenance superior to traditional membranes, facilitating predictable bone augmentation. Implant therapy success, however, depends on multiple factors: materials science, precise atraumatic surgery, reverse prosthetic planning, and rigorous long-term patient follow-up. Advancements in bioactive surfaces and patient-specific digital regeneration will build on these foundations, enhancing predictability, esthetics, and longevity in prosthetic outcomes.

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