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Osseointegration in Oral Implantology: Biological Phases, grafts Success Criteria, and Prevention of Complications, A Comprehensive Review

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Abstract

Background: Osseointegration is the intimate biological connection between bone and a load-bearing implant which is the cornerstone of modern implant dentistry. When bone volume or quality is inadequate, graft materials are required to reconstruct the alveolar ridge and provide a stable host bed. Over the past three decades, xenografts, alloplastic substitutes, bovine-derived matrices, and coral-based scaffolds have been explored as alternatives to autogenous bone. In light of these developments, the present review synthesizes experimental and clinical evidence to elucidate the biological phases of osseointegration, establish measurable success criteria, and compare the biological behavior, strengths, and limitations of the four major graft categories, while further highlighting preventive strategies to reduce biological and mechanical complications. **Methods:** PubMed, Scopus, and Web of Science, 1980-April 2025, were searched to conduct the systematic narrative review. Keywords were osseointegration, dental implant, xenograft, bovine graft, alloplastic graft and coral graft. The inclusion criteria were restricted to peer-reviewed studies with English language reporting histological, radiographic or biomechanical outcomes. **Results:** Long-term dimensional stability was provided by xenograft and bovine materials, remodeling was slowed; alloplastic grafts were found to turnover more quickly and have higher early bone formation; coral-derived scaffolds were found to provide natural porosity but have limited mechanical strength. When properly handled all materials were biocompatible. **Conclusion:** The graft classes have a unique role to play in bone regeneration. Effective osseointegration requires balancing between material properties and defect morphology, precision of surgery and host healing. There is still necessity of standardized long-term studies with the aim of perfecting the material choice.

Introduction:

Since Branstake described it first in 1969, the concept of osseointegration has developed out of an easy mechanical concept into a complicated biological phenomenon whereby new bone becomes structurally continuous with titanium surface (1). At the microscopic level, the condition is direct bone-to-implant contact without an interposed soft tissue. Clinically it is manifested as a pain free, immobile implant that can withstand functional loading (2). Effective integration entails a balance between the method of surgery, implant design, and the regenerative response of the host. Osseointegration refers to a direct structural and functional connection between newly formed bone and the surface of load bearing dental implant (3). Successful osseointegration has been clinically defined as no movement of the implants, preservation of marginal bone levels and functional stability during occlusal loads over a long period. The alveolar ridge suffers a loss of up to 50% volume up to six months following extracting of teeth (4). Primary stability and esthetics are compromised by such resorption. Bone augmentation procedures rebuild the ridges, preserves contours and enables optimal placement of the implants (5). In spite of the biological gold standard- autogenous bone, small amounts and donor site morbidity has increased the availability of substitutes with comparable osteoconductive and osteoinductive properties (6). Grafts may be classified in terms of origin: allograft, alloplast, xenograft and autograft. Among the xenograft family, clinical practice is predominantly composed of bovine-derived materials, coral scaffolds, originally marine skeletons that have been converted to calcium phosphate, representing natural porous analogue (7). Synthetic alloplasts, like β-tricalcium phosphate (β-TCP), hydroxyapatite (HA), and bioactive Glass have regulated chemistry and degradation profules (8). In material selection, it is necessary to comprehend the interaction of each type with host biology in the process of osseointegration. Osseointegration continues to follow a series of overlapping and interdependent phases: hemostasis, inflammation, angiogenesis, osteogenesis, and bone remodeling (9,10). All phases are rigorously controlled through molecular signal pathways, and very sensitive to surgical trauma, implant surface characteristics, local vascularity, and systemic health status. Based on this, the biological processes leading to osseointegration are sequential and overlapping, and determined by the composition of the graft, surface characteristics, and mechanical properties. Although all types of grafts stimulate bone healing, their remodeling rates vary, xenograft and bovine grafts give the body a long-term stable state, alloplasts participates quickly in remodeling, and coral grafts balances the resorption and formation of new bone, Table (1).

Hemostasis and Early Fibrin Matrix Formation

Implant surface micro topography is very critical at this stage. Titanium surfaces of moderately roughness improve the fibrin retention and platelet activation, which promotes early biological stability, and facilitates the late formation of bones (11). Surgical trauma immediately after the implantation process disrupts the local vasculature, which leads to platelet aggregation and clotting of the bone-implant interface. This provisional matrix of fibrin is used to stabilize the implant and provides a scaffold on which the cellular migration and the growth factor release take place (12).

Inflammatory Phase

The inflammatory stage starts a few hours following the placement of implants, and entails the recruitment of neutrophils and macrophages. The cells clear necrotic debris and bacterial contaminants and release the cytokines and chemokines, which coordinate angiogenesis and the recruitment of osteoprogenitor cells (13). Normal healing depends on a regulated inflammatory response but prolonged or excessive inflammation, which is typical of surgical trauma or microbial contamination, can suppress osteoblast

differentiation and undermine osteointegration. Hassan and Al-Bayati showed that particular patterns of microbes are strongly related to the early implant infections, which is why strict aseptic technique and early diagnostics are very significant (14).

Angiogenesis and Osteogenesis

Angiogenesis is another important step in the osseointegration cascade, because the newly formed blood vessels deliver oxygen, nutrients, and signaling molecules required for the regeneration of bones (15). Under-vascularization can lead to ischemia, delayed healing, and increase in the risk of graft failure. Osteogenesis involves the differentiation regarding mesenchymal stem cells into osteoblasts, osteoid matrix deposition followed by mineralization. Initially, the woven bone forms in a rapid way around the implant surface, and this gives early mechanical anchorage. This immature bone is then remodeled into lamella bone with superior structural organization as well as mechanical strength (16). According to Al-Dabagh and Al-Mashhadani, the thickness of buccal bone plate is a powerful indicator of early implant stability, and inadequate buccal bone could undermine osteogenesis despite seemingly good primary stability (12). Every graft material influences these stages differently by controlling ion release, porosity, and mechanical stability (17**).** According to Albrektsson (2) and Buser (18), implant success requires absence of pain or infection, mobility = 0, bone loss < 1.5 mm in the first year and < 0.2 mm annually thereafter. Histologically, high bone-to-implant contact (BIC %) and abundant new bone formation area (NBFA %) indicate biological success (19, 20). Biological complications include infection, inadequate vascularization, or excessive micromotion leading to fibrous encapsulation (5). Mechanical problems, over-loading, malposition, or poor implant design may also compromise osseointegration. Graft-specific issues such as delayed resorption or exposure must be anticipated. Despite hundreds of experimental and clinical studies discuss bone substitute materials in implant dentistry, integrated and direct comparisons among xenograft, alloplastic, bovine, and coral grafts with respect to their influence on osseointegration remain limited and scattered. This review aims to consolidate available evidence to clarify the biological phases of osseointegration, define measurable criteria for implant success, and compare the biological behavior, advantages, and limitations of these four major graft categories. Furthermore, the review provides an evidence-based framework to aid clinicians and researchers in understanding graft-related biological and mechanical complications and emphasizes preventive strategies that may contribute to improved implant stability and long-term clinical outcomes.

Methodology

Study design, period, and setting

This work was conducted as a structured narrative review of previously published studies, rather than an original experimental or clinical investigation. The review was carried out within an academic research setting in the field of dental implantology at Mustansiriyah University, College of Dentistry. The literature search, study selection, and data extraction processes were performed between August 2024 and October 2025.

Search strategy

Electronic searches were conducted in **PubMed**, **Scopus**, and **Web of Science**, using Boolean operators:

(osseointegration and dental implant) and (xenograft or bovine graft or alloplastic graft or coral graft).

Reference lists of retrieved papers and major reviews were manually screened to identify additional sources.

Inclusion criteria:

a) In vivo animal or human studies assessing implants with xenograft, alloplastic, bovine, or coral grafts.
b) Quantitative outcomes: BIC %, NBFA %, radiographic bone gain, implant stability (ISQ), or torque tests.

c) Controlled or comparative designs with healing ≥ 2 weeks.

Exclusion criteria:

a) Studies using solely autografts/allografts.
b) Case reports lacking quantitative data.
c) Non-English publications or conference abstracts without full text.

Data extraction and analysis

For each study, the following information was extracted: author + year, study model, graft composition, method of evaluation, healing time, and main histologic or radiographic results. Due to heterogeneity in protocols, a qualitative narrative synthesis was chosen instead of meta-analysis.

Results

Biological behavior of Xenografts in implantology

Xenografts are bone substitutes of non-human origin, most frequently bovine or porcine, rendered non-antigenic through high-temperature deproteinization and sterilization (6, 21). The remaining mineral structure resembles natural hydroxyapatite with interconnected pores that facilitate cell adhesion and vascular infiltration (22). Histologically, new bone forms directly on the particle surface through creeping substitution, and the graft acts as a long-term space maintainer (15, 23). Although resorption is slow, the material integrates predictably without inflammatory response (24).

Evidence synthesis

Xenografts provide stable volume but delayed remodeling compared with autogenous bone. In animal and human trials, residual granules may remain after years yet remain vitalized by osteocytes (25). Removal-torque and resonance-frequency analyses consistently confirm mechanical stability equivalent to natural bone (26). Overall, xenografts remain the benchmark for socket preservation and sinus augmentation, Table (2). Xenografts ensure biocompatibility and dimensional stability, but clinicians must anticipate slow resorption and consider ethical constraints when choosing animal-derived materials

Biological behavior of Alloplastic (Synthetic) grafts in implantology

Alloplastic materials are synthetic ceramics such as β-tricalcium phosphate (β-TCP), hydroxyapatite (HA), biphasic calcium phosphate, and bioactive glass. They are fully biocompatible and their microstructure can be engineered to control porosity and resorption (8, 27). Degradation liberates calcium and phosphate ions that stimulate osteoblast activity and mineralization (28). Modern β-TCP/HA composites achieve balanced resorption and volume stability (29).

Evidence synthesis

Animal experiments demonstrate that β-TCP dissolves gradually, allowing lamellar bone to replace it within weeks. Flifl et al, (30) reported higher osteoprotegerin (OPG) expression and lower residual material in β-TCP/$CaSO_4$ groups than in bovine xenografts. Human clinical series show up to 85 % resorption within 33 weeks with simultaneous bone formation (31). Despite its synthetic origin, alloplastic material elicits no immune response and is appropriate for patients who decline animal products (32), Table (3). Alloplasts are safe and controllable but mechanically fragile and should be protected from early functional stress to avoid collapse before bone bridging.

Biological behavior of Bovine-Derived grafts in implantology

Bovine-derived grafts, such as Bio-Oss® and Cerabone®, are purified mineral matrices processed from cow bone. Their crystallographic composition and pore structure closely match human cancellous bone (6, 21). They exhibit high surface energy and interconnected pores that encourage osteoconduction and vascularization (29).

Evidence synthesis

Histologic evaluations reveal close contact between new bone and residual particles with no inflammatory infiltrate (33).

Araujo and Lindhe (34) showed that bovine granules in dogs exhibited delayed yet continuous bone formation. In long-term human biopsies, some residual particles become vitalized by osteocytes through canaliculi (33). Clinical survival rates of implants placed in DBBM-augmented sites exceed 95 % over ten years (18,24), Table (4). Bovine grafts offer predictable clinical performance and excellent volume preservation. Their persistence within the bone matrix requires careful interpretation during radiographic evaluation to avoid misdiagnosing residual particles as pathology.

Biological behavior of Coral (Coralline) grafts in implantology

Coral-derived scaffolds originate from marine coral (Porites species) whose calcium-carbonate skeletons are hydrothermally converted to hydroxyapatite while retaining their interconnected porosity (7). This natural architecture closely mimics cancellous bone and supports rapid vascular ingrowth and osteoblast migration (35, 36). Although mechanically brittle, their biocompatibility is excellent and they gradually resorb as they are replaced by new bone.

Evidence synthesis

In early work, White et al. (35) documented direct osteoid deposition along coral pore walls without fibrous encapsulation. Roy and Lin (16) showed that hydrothermally converted coral was more stable than pure $CaCO_3$. Recent studies confirmed around 40 % new bone formation at 8 weeks Fouad et al (36) and significant enhancement when combined with mesenchymal stem cells (37). Zizzari et al. (38) and Zuo et al. (39) emphasized coral's potential as a template for bioactive composite development, Table (5). Coral grafts are highly biocompatible and promote rapid bone ingrowth but their brittleness limits load-bearing applications. Ongoing research combining coral with biopolymers or growth factors aims to overcome these constraints.

Discussion

Integrating the Biological Evidence

Across experimental and clinical investigations, osseointegration consistently follows the same fundamental biological sequence., hemostasis, inflammation, osteogenesis, and remodeling, although different graft materials modulate the rate and quality of these stages in distinct ways (Figures 1 and 2). Xenograft and bovine-derived materials primarily function as space maintainers, preserving ridge volume by resisting resorption but integrating at a slower pace (6,15, 24). In contrast, alloplastic substitutes such as β-tricalcium phosphate or biphasic calcium phosphate promote rapid ionic exchange, which enhances early osteoblast differentiation and bone turnover (28, 30). Coral-based scaffolds, owing to their natural three-dimensional porous architecture, facilitate vascular penetration and early new-bone deposition; however, their limited mechanical strength restricts their use in load-bearing regions (7, 37).

Biomechanical Integration

Mechanical anchorage is the visible manifestation of histologic osseointegration. Studies using removal-torque testing and resonance-frequency analysis (RFA) demonstrated no significant differences among graft types after the healing phase (26). This indicates that once new bone forms at the interface, the origin of the scaffold becomes less critical; the *quality* of regenerated bone and implant macro-design play greater roles in long-term load transfer (19, 22).

Clinical Relevance of Graft Material Properties

Clinically, xenografts and bovine grafts remain the materials of choice for sinus augmentation and ridge preservation. (18,29). Alloplastic materials are advantageous for small to moderate defects or for patients who prefer synthetic, animal-free options (40). Coral grafts are most suitable for non-stress-bearing sites or as carriers for biologically active molecules such as BMP-2 or PRF (37, 39). The decisions of the clinician must balance biological remodeling and mechanical stability as well as establishing

ethics. The histological assessment of bone response covering the surface of the implant and surrounding the graft materials showed clear patterns at four weeks post-surgery. The existence of bone graft particles (BG) closely surrounded by newly formed bone (NB) and bone marrow spaces (BM) with toluidine blue staining which is an early sign of bone remodeling activity near the implant surface (IM). Bone formation in the Algipore and biphasic graft groups was comparatively low and made up primarily of immature woven bone (WB) with incomplete incorporation of the graft particles with the bone-implant interface. In contrast, specimens that were subjected to bone-marrow-derived mesenchymal stem cells (BMSCs) showed increased new bone deposition, signatures of early maturation to lamellar bone (LB), and enhanced continuity of the bone-implant contact zone. All these histological findings indicate that there was an increased early osseointegration and accelerated bone maturation within the BMSC-treated groups which complied with the results obtained by Tseng et al. (40). These histological features and comparative bone responses of the experimental groups are shown in Figure (1). SEM analysis showed that there was a difference in surface morphology and porous structure of the Algipore and biphasic bone graft materials as the magnification achieved was increased (×100, ×1000, ×2000 and ×4000). Under lower magnification, irregular granule morphology of both graft materials was seen with well defined macrostructural features. As the magnification was increased, a porous network that was well formed and interconnected was observed. Algipore displayed a more homogenous surface with rounded and evenly distributed pores and the biphasic graft showed more heterogeneous surface morphology indicated by variable pore sizes and rough surface roughness. The existence of the micro- and nanoporous structures was especially evident at the magnifications of ×2000 and ×4000, which are thought to be essential in cellular adhesion, vascular infiltration, and osteoconductive activities. All these SEM observations indicate significant variations in the surface topography and porosity of the two graft materials which could affect their biological efficacy and bone regenerative capacity as reported by Tseng et al. (40). Figure 2 gives the example SEM images at the various magnifications that depict these morphological features.

Mechanical and Biological Failures

During initial healing, mechanical overloading disrupts bone formation and can lead to the fibrous encapsulation of the implant instead of true osseointegration. This danger is also especially pronounced in grafted areas with the support of rapidly resorbing materials or with bone quality being impaired (41).

Graft-Related Implant Complications

In a study, Al-Dabagh and Al-Mashhadani emphasized that the insufficient thickness of the buccal bone plates is a significant risk factor that leads to the early development of implant instability, followed by the marginal bone loss, thus emphasizing of enough bone volume as well as prosthetically driven implant positioning throughout planning the treatment (12). A deficiency in the support of the bones does not only undermine primary stability but it also predisposes implants and grafted sites to various biological and mechanical complications. Such complications could be caused by both postoperative and surgical factors such as flap tension, thin soft tissues, microbial contamination as well as the premature functional loading. These factors may be clinically presented in the form of wound dehiscence and graft exposure, postoperative infection, graft failure, and implant failure, sinus membrane perforation during maxillary procedures, mechanical overload that leads to the development of a fibrous tissue rather than to the formation of an osseointegration, and peri-implantitis, which is accompanied by the accumulation of plaque and progressive bone loss. All these data points towards that meticulous surgical method, sufficient bone mass, and proper postoperative management care can help to reduce the number of complications and maximize the long-term success of implants, Table (6).

Prevention Strategies

The key to successful implant therapy and graft integration is still prevention. The preventive measures are focused on limiting surgical trauma, optimize soft tissue conditions, improve vascularization, and decrease microbial contamination (42). CBCT-based planning and extensive preoperative assessment enables precise anatomical constraints identification and facilitates prosthetically driven implant placement. The sufficient keratinized mucosa width, no tension during the flap closure, and the proper choice of graft also allow mitigating the risk of biological complications (43), Table (7).

Treatment Approaches

Management of implant- and graft-related complications needs a case specific as well as biologically driven method. Early intervention is necessary to avoid the progression regarding tissue destruction as well as the irreversible implant failure (44). The interventions are conservative approaches including plaque control, antiseptic rinses, and systemic antibiotics to surgical procedures including flap revision, graft removal and regenerative procedures. Treatment depends on severity of complication, biological state of tissues and risk factors of a patient (45).

Limitations of the Current Evidence

Although there are an extensive number of data, heterogeneity of models, time of healing, and approaches of analysis is high. The majority of the histologic studies are not long-term (less than 1 year) and based on a low sample size. There are very few randomized controlled clinical trials that directly compare these graft types under standardized protocols. Future investigations should incorporate micro-CT, histomorphometry, and implant-stability metrics to create a unified evidence base.

Future Directions

The next generation of bone substitutes is moving toward biofunctionalized composites:

a) Doping β-TCP or HA with osteogenic ions (Sr, Zn, Si) for enhancing cell signaling (21).

b) Hybridizing coral scaffolds with collagen or polymers for improving the mechanical strength (38).

c) Developing smart biomaterials that release growth factors in controlled way (46).

Conclusions

1. The long-term success of dental implant therapy is based on the process of osseointegration that is dynamic and is biologically regulated and relies on the interactions between host bone biology, implant surface properties, surgical technique, graft material behavior, and postoperative care.

2. The development of bone-implant integration follows a series of biological steps, and the disruptions in any of the stages can disrupt the stability of the implants and cause higher chances of failure.

3. Bone graft materials differ markedly in biological behavior and clinical indications: xenograft and bovine grafts provide superior dimensional stability, alloplastic grafts demonstrate faster remodeling, and coral-derived materials support early bone formation in selected non–load-bearing situations.

4. Accurate assessment using combined clinical, radiographic, and biomechanical evaluation is essential for monitoring osseointegration and optimizing treatment outcomes.

5. Long-term implant success relies primarily on appropriate case selection, respect for biological healing principles, and precise surgical execution rather than on graft origin alone.

Conflicts of Interest:

The authors have no conflicts of interest.

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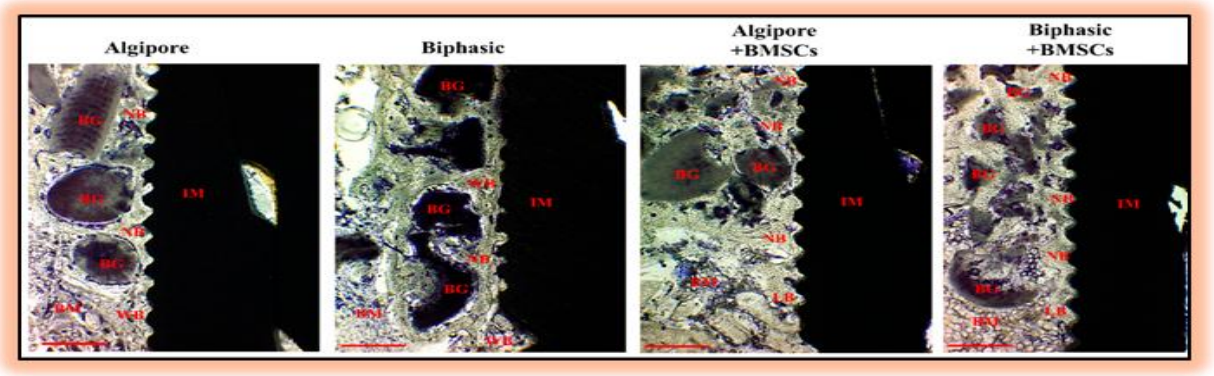

Figure 1: Histological analysis of newly formed bone around bone graft materials and implants among groups four weeks after surgery. Toluidine blue stain, bone graft (BG), new bone (NB), woven bone (WB), lamellar bone (LB), implant (IM), and bone marrow (BM). Original magnification ×40. Scale bar: 500 μm. By Tseng, K-F., et al, 2024 (40)

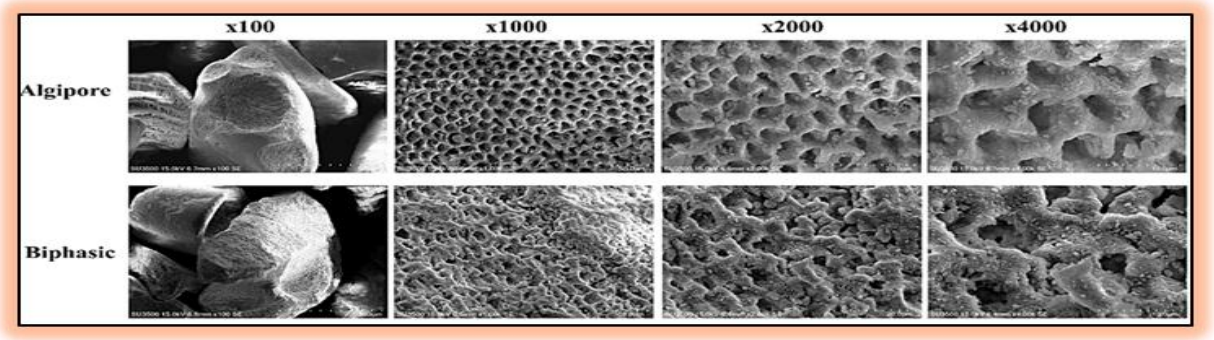

Figure 2: Scanning electron microscopic images of the porous structure of bone graft materials at different magnifications (×100, ×1000, ×2000, ×4000). By Tseng, K-F., et al, 2024 (40).

Table 1: Comparative summary of osseointegration phases, associated biological processes, Material-Dependent Influences and the differential effects of graft materials on peri-implant bone regeneration, with supporting in vivo and clinical studies (with Key References)

Phase	Main Biological Events	Key Cellular / Molecular Activities	Influence of Graft Material and Supporting Studies
1. Hemostasis	Formation of a fibrin clot immediately after implant placement, providing a temporary matrix for healing.	Platelet activation and release of PDGF, TGF-β, and VEGF initiate repair cascade.	Surface micro-roughness enhances clot adhesion and fibrin stabilization. β-TCP and coral HA show superior fibrin entrapment (Davies, 2003 (22); Smeets et al., 2016 (48). Xenograft microporosity facilitates early coagulum retention (Schlegel and Donath, 1998 (6).
2. Inflammation	Migration of neutrophils and macrophages to the surgical site to clear debris and signal new tissue formation.	Cytokines (IL-1β, TNF-α) attract osteoprogenitor and endothelial cells; inflammatory mediators activate angiogenesis.	Deproteinized bovine xenografts evoke minimal immune reaction (Piattelli et al., 1999 (15). Alloplastic materials trigger mild, transient inflammation beneficial for remodeling (Flifl et al., 2022 (30); Ashfaq et al., 2024 (47).
3. Angiogenesis & Proliferation	Formation of new capillaries within the fibrin matrix; fibroblasts deposit collagen framework.	Endothelial cell sprouting mediated by VEGF and FGF-2; fibroblast proliferation supports matrix formation.	Coral and porous HA scaffolds promote vascular penetration via inter-connected pores (Roy and Lin, 1999(7); Fouad et al., 2018 (36). β-TCP degradation releases Ca^{2+} ions that stimulate endothelial migration (Wang et al., 2019 (28).
4. Osteogenesis	Mesenchymal stem cells differentiate into osteoblasts; osteoid matrix and early woven bone appear.	Osteoblasts express alkaline phosphatase, osteocalcin, and osteopontin; initial mineralization begins.	Alloplasts enhance osteoblast differentiation through ionic exchange (Li et al., 2015 (49); Flifl et al., 2022 (30). Xenograft scaffolds support appositional bone growth along particle surfaces (Orsini et al., 2011 (33); Inchingolo et al., 2025(8).
5. Remodeling and Maturation	Woven bone gradually replaced by lamellar bone oriented with functional stress; bone density increases.	Coupled osteoclast–osteoblast activity remodels bone; maturation aligns trabeculae with load.	Bovine xenografts maintain long-term volume but remodel slowly (Hamada et al., 2015 (50); Calvo-Guirado et al., 2021(29). β-TCP resorbs faster, allowing lamellar substitution (Titsinides et al., 2019 (27). Coral graft resorption parallels bone deposition for balanced turnover (Sari et al., 2022 (37); Zuo et al., 2023(39).

Table 2: Representative Evidence on Xenograft Materials

Year	Author(s)	Model / Design	Material	Key Methods	Main Findings
2025	Inchingolo et al. (24)	Human long-term follow-up	Bovine xenograft	Histology	10–30% residual mineral after >3 years
2024	Guler et al. (26)	Rat tibia	Bovine xenograft vs synthetic	Torque test, histology	Comparable mechanical stability
2015	Venkataraman et al. (25)	Review	Bovine xenograft	Literature synthesis	Stable ridge volume; slow turnover
2001	Yildirim et al. (23)	Human biopsies	DBBM	Light microscopy	Residual particles vitalized by osteocytes
1999	Piattelli et al. (15)	Human sinus lift	DBBM	Histomorphometry	Direct bone–particle contact; slow resorption
1998	Schlegel and Donath (15)	Canine mandible	Deproteinized bovine bone (DBBM)	Histology & TEM	Excellent osteoconduction; no foreign-body reaction
1989	Schlegel and Donath (55)	Mandibular defects	Deproteinized bovine bone	Histology & SEM	High osteoconductivity; absence of foreign-body reaction
1986	Klinge et al. (54)	Animal model	Natural bovine bone mineral	Light microscopy	Slow resorption; maintained space for bone regeneration
1983	Levin et al. (53)	Canine alveolar defects	Deproteinized bovine bone	Histology	Stable graft integration; gradual new bone formation
1980	Nery et al. (52)	Human periodontal defects	Bovine bone mineral	Histology	Biocompatible scaffold; osteoconductive bone ingrowth; minimal inflammation

Table 3: Representative Evidence on Alloplastic Materials

Year	Author(s)	Model / Design	Material	Key Methods	Main Findings
2025	Sleman et al. (32)	Review	Synthetic grafts	Meta-review	Emerging bio-ion-doped materials
2024	O'Hoolley et al. (31)	Human cases	β-TCP/$CaSO_4$	Histology	85% resorption with lamellar bone
2022	Flief et al. (30)	Rabbit tibia	β-TCP/$CaSO_4$	Histology, OPG immunostain	Fast integration; lowest residual graft
2019	Titsinides et al. (27)	Rabbit skull	β-TCP vs bovine xenograft	Histomorphometry	45% new bone vs 32% in xenograft
2015	Li et al. (49)	Rat calvaria	β-TCP	Histology + cell count	High osteoblast/osteoclast ratio
2003	LeGeros et al. (8)	Rabbit femur	β-TCP	Histology	Rapid osteoid deposition and complete resorption
1989	LeGeros (59)	Review	Calcium phosphate ceramics	Literature synthesis	Established β-TCP as resorbable, osteoconductive scaffold
1987	Hulbert et al. (58)	Experimental bone defects	Porous calcium phosphate	Histology	Interconnected porosity promoted vascular and bone ingrowth
1984	Klein et al. (57)	Canine bone defects	β-TCP	Histology	Progressive resorption with replacement by new bone
1983	LeGeros et al. (56)	Animal model	Calcium phosphate ceramic (β-TCP)	Histology	Demonstrated bioactivity and osteoconductive bone ingrowth

Table 4: Representative Evidence on Bovine-Derived Materials

Year	Author(s)	Model / Design	Material	Key Methods	Main Findings
2021	Zhao et al. (21)	Review	Bovine xenografts	Systematic review	Most widely used; slow resorption
2015	Hamada et al. (50)	Human biopsy	Bovine xenograft	Histology	No inflammation after 5 years
2011	Orsini et al. (33)	Human sinus	Bio-Oss Collagen	Histology	Residual particles vitalized by osteocytes
2005	Araujo and Lindhe (34)	Dog socket	Bio-Oss®	Histology	Delayed yet steady bone formation
1998	Schlegel and Donath (6)	Dog mandible	DBBM	Histology	Excellent osteoconduction; slow remodeling
1989	Schlegel and Donath (55)	Experimental mandibular defects	Deproteinized bovine bone	Histology & SEM	High osteoconduction; no foreign-body reaction
1986	Klinge et al. (54)	Animal model	Natural bovine bone mineral	Light microscopy	Slow resorption with stable scaffold function
1983	Levin et al. (53)	Canine alveolar defects	Bovine-derived bone	Histology	Gradual bone replacement; minimal inflammatory response
1980	Nery et al.(52)	Human periodontal defects	Bovine bone mineral	Histology	Good biocompatibility and osteoconductive bone growth

Table 5: Representative Evidence on Coral and Coralline Materials

Year	Author(s)	Model / Design	Material	Key Methods	Main Findings
2023	Zuo et al. (39)	Review	Coral-based biomaterials	Systematic review	Promising bio-hybrid platform
2022	Sari et al. (37)	Rabbit tibia	Coral HA + MSCs	Micro-CT, histology	Enhanced mineralization
2019	Park et al. (51)	Rabbit radius	Coral HA + polymer	Micro-CT	Improved mechanical strength
2018	Fouad et al. (36)	Rabbit calvaria	Coral HA	Histology	≈40% new bone at 8 weeks
1999	Roy and Lin (7)	Rat calvaria	Coralline HA vs $CaCO_3$	Histology	HA form more stable and osteoconductive
1986	White et al. (35)	Dog femur	Natural coral HA	Histology	Bone ingrowth without fibrous tissue
1985	White et al. (62)	Dog femur	Natural coral HA	Histology	Progressive bone penetration without fibrous encapsulation
1983	Roy et al.(61)	Rabbit bone defects	Coralline calcium carbonate	Histology	Interconnected porosity favored osteoconduction
1981	Holmes et al. (60)	Canine femur	Natural coral ($CaCO_3$)	Histology	Coral acted as a biocompatible scaffold allowing bone ingrowth

Table 6: Common Complications in Implant and Graft Procedures

Complication Type	Primary Cause	Clinical Consequences
Wound dehiscence	Flap tension, thin mucosa	Graft exposure, infection
Infection	Microbial contamination	Graft failure, implant loss
Sinus perforation	Thin Schneiderian membrane	Sinusitis, graft migration
Mechanical overload	Premature loading	Fibrous encapsulation
Peri-implantitis	Plaque accumulation	Progressive bone loss

Table 7: Preventive Measures in Implant and Graft Procedures

Preventive Goal	Strategy	Biological Rationale
Reduce trauma	Atraumatic surgery	Preserves blood supply
Prevent infection	Aseptic technique, antibiotics	Controls microbial load
Improve stability	Delayed loading	Allows bone maturation
Enhance angiogenesis	Use of PRF / I-PRF	Promotes vascular growth
Maintain soft tissue	Flap design optimization	Prevents ischemia

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