

**Ministry of Higher Education and
Scientific Research College of Dentistry
Al-Mustaqbal University**



Type of effectiveness of bone graft use in oral and maxillofacial resurgery

*A Research Study Submitted in Partial Fulfillment of the Requirements for the
Degree of Bachelor of Dental Surgery (B.D.S.)
College of Dentistry Al-Mustaqbal University*

Prepared by:

Ghaidaa Waleed Awad

Aya Fares Jawad

Fatima Imad Najm

Kawthar Raheem Akreem

Shahad Hussam Hamad

Fatima Turki Hamoud

Supervised by:

Dr. Mohammed Ali Shaalan

بِسْمِ اللّٰهِ الرَّحْمٰنِ الرَّحِیْمِ

فِي اللّٰهِ مَعْنٰكُمُ الْوَالِدِ الْكَرِيمِ
بِسْمِ اللّٰهِ الرَّحْمٰنِ الرَّحِیْمِ

صدق الله العلي العظيم

سورة المجادلة الآية (11)

Dedication

We dedicate this research to our parents, whose endless love, patience, and support have been the foundation of our success.

We also dedicate it to our families and friends for their constant encouragement and belief in us throughout our academic journey.

Finally, we dedicate this work to everyone who supported us and contributed, directly or indirectly, to the completion of this research.

Acknowledgements

We would like to express our sincere gratitude and appreciation to the Deanship of the College of Dentistry at Al-Mustaqbal University for providing the academic environment and facilities that supported the completion of this research.

We also extend our deepest thanks to the teaching staff of the College of Dentistry for their valuable knowledge, guidance, and continuous support throughout our years of study.

Our special and heartfelt thanks go to our research supervisor, Dr. Mohammed Ali Shaalan, for his scientific guidance, constructive feedback, patience, and constant encouragement, which played a crucial role in accomplishing this work.

Finally, we would like to thank everyone who contributed directly or indirectly to the completion of this research.

Supervisor's Certification

I certify that this graduation research project entitled:

“Type of effectiveness of bone graft use in oral and maxillofacial surgery”

submitted by the students:

(Ghaidaa Waleed Awad, Aya Fares Jawad, Fatima Imad Najm, Kawthar Raheem Akreem, Shahad Hussam Hamad, Fatima Turki Hamoud)

of the College of Dentistry, Al-Mustaqbal University, has been carried out under my supervision. I affirm that it is an original work of the students and has been completed in accordance with the academic requirements of the College of Dentistry.

Supervisor

Name: Dr. Mohammed Ali Shaalan

Academic Title: _____

Signature: _____

Date: _____

TABLE OF CONTENTS

No.	Title	Page
I	Abstract	X
II	Introduction	1
	a. Background	1
	B. Aims and Objectives	2
III	Classification of Bone Grafts	3
	a. Autografts	4
	b. Allografts	5
	c. Xenografts	6
	d. Alloplastic Grafts	7
IV	Clinical Applications	9
	a. Dental Implants	9
	b. Ridge Augmentation	10
	c. Trauma and Tumors	11
	d. Congenital Defects	11
V	Effectiveness Evaluation	13
	a. Bone Volume Stability	13

	b. Osseointegration	15
	c. Healing Time	16
	d. Long-term Success Rates	17
VI	Factors Affecting Outcomes	18
	a. Patient-Related Factors	18
	b. Surgical Technique	19
	c. Material Properties	19
VII	Complications	22
	a. Infection	22
	b. Graft Failure	23
	c. Donor Site Morbidity	24
VIII	Adjunctive Therapies	25
	a. Platelet-Rich Fibrin (PRF)	25
	b. Bone Morphogenetic Proteins (BMPs)	26
	c. Other Biological Agents	27
IX	Advanced Technologies	29
	a. Three-Dimensional Printing	29
	b. Tissue Engineering	32
	c. Stem Cell Therapies	32

X	Clinical Indications for Bone Grafting and Sinus Lift	33
XI	Clinical Guidelines and Recommendations	35
XII	Limitations and Challenges	36
XIII	The Perspectives Of The Future	37
XIV	Conclusion	38
	References	40

LIST OF FIGURES

Figure Number	Title	Page
Figure 1	Figure 1: Stages of bone healing showing hematoma formation, fibrocartilaginous callus formation, callus ossification, and bone remodeling.	3
Figure 2	Classification and Biological Properties - Hierarchical classification of all bone graft material types with their biological characteristics	5
Figure 3	Maxillary Sinus Augmentation Using Xenograft Material	10
Figure 4	Clinical application of PRF in soft tissue healing after dental procedure	12

Figure Number	Title	Page
Figure 5	Autogenous Mandibular Block Graft for Ridge Augmentation	14
Figure 6	Comparison of success rates (%) and healing time (weeks) among different bone graft materials.	15
Figure 7	Long-term implant survival rates over 5 years for different bone graft Material	21
Figure 8	Comparison of complication rates among different bone graft materials	21
Figure 9	Bone Loss After Tooth Extraction and the Role of Bone Grafting	23
Figure 10	Preparation and Clinical Applications of Sticky Bone Using PRF and Bone Graft	28
Figure 11	Workflow of Customized 3D-Printed Implant for Mandibular Reconstruction	30
Figure 12	Bone grafting and sinus lift procedures prior to dental implant placement	34

I. ABSTRACT

Bone defects in the oral and maxillofacial region represent a significant clinical challenge due to their impact on both function and aesthetics. Bone grafting has emerged as a fundamental approach for the reconstruction of these defects, utilizing a variety of materials with distinct biological and clinical properties.

This literature review aims to evaluate the different types of bone grafts used in oral and maxillofacial reconstruction and to assess their effectiveness based on current scientific evidence. A comprehensive search was conducted using major databases, including PubMed, Google Scholar, and ScienceDirect, focusing on studies published within the last decade. Priority was given to clinical trials, systematic reviews, and meta-analyses.

The findings indicate that autogenous bone grafts remain the gold standard due to their superior osteogenic potential and biological compatibility. However, alternative graft materials such as allografts, xenografts, and alloplastic substitutes offer reliable outcomes with reduced morbidity and increased availability. In addition, adjunctive therapies and advanced technologies, including growth factors and tissue engineering approaches, have shown promising improvements in bone regeneration and clinical success.

In conclusion, the selection of an appropriate bone graft material should be based on the clinical situation, defect characteristics, and patient-related factors. Continuous advancements in biomaterials and regenerative techniques are expected to further enhance treatment outcomes in oral and maxillofacial reconstruction.

Keywords: Bone graft, oral reconstruction, maxillofacial surgery, bone regeneration, osseointegration, biomaterials

II. INTRODUCTION

A. Background

Bone is living tissue that can sustain and repair itself. However, major bone defects from injury, surgical removal, congenital defects, or disease go beyond the body's natural healing ability. One of the biggest challenges facing the surgical community is the restoration of bone volume and function in the jaw and face. This is critical for the functional, aesthetic, and quality of life improvement for the patient.

Bone grafting is recognized as the most effective way to treat these volumetric deficiencies. Bone grafts's biological success is reliant on three mechanisms: osteogenesis (the new bone formation by osteogenic cells), osteoconduction (where a scaffold is provided for bone formation), and osteoinduction (where a signal is provided that recruits and differentiates osteogenic cells) . For effective prediction of the clinical outcomes and selection of the graft materials, these biological principles must be understood [1].

The complexity of the anatomy and function of the oral and maxillofacial region poses distinct challenges for bone reconstruction. In contrast to other skeletal structures, the mandible and maxilla provide osseointegrated dental supports, experience intricate and multifaceted biomechanical loading conditions, and necessitate detailed and exact reconstructive surgery for the preservation of the facial aesthetics and functionality. All of the aforementioned factors contribute to the challenges in choosing the appropriate materials and planning the surgical procedure [2].

B. Aims and Objectives

This literature review intends to achieve the following eight objectives:

1. Identify and describe the biological and clinical characteristics of the various currently available bone graft materials used in the reconstruction of the jaws and associated structures.
2. Understand the different types of grafts and their effectiveness as it relates to their success, bone formation, osseointegration and stability over time.
3. Understand the various application of bone grafts in different domains of oral and maxillofacial surgery.
4. Identify and describe the various outcomes related to different patients, their surgical dilemma, and the grafting materials used.
5. Identify and describe adjunctive therapy strategies which may accelerate the rate of bone formation, especially the use of platelet rich fibrin and bone morphogenetic proteins.
6. Identify and describe the use of innovative technologies like 3D printing and tissue engineering.
7. Describe the analyses of the various strategies in order to enhance clinical efficiency.
8. Collate available literature to describe evidence-based guides to practice, and identify gaps in order to drive future research.

III. CLASSIFICATION OF BONE GRAFTS

Bone graft materials represent diverse biologically active and biocompatible materials designed to replace missing bone and facilitate regeneration. Contemporary classification systems distinguish materials based on their biological origin and mechanisms of action [1]. Figure 1 illustrates the fundamental bone healing mechanisms that underpin graft selection and performance.

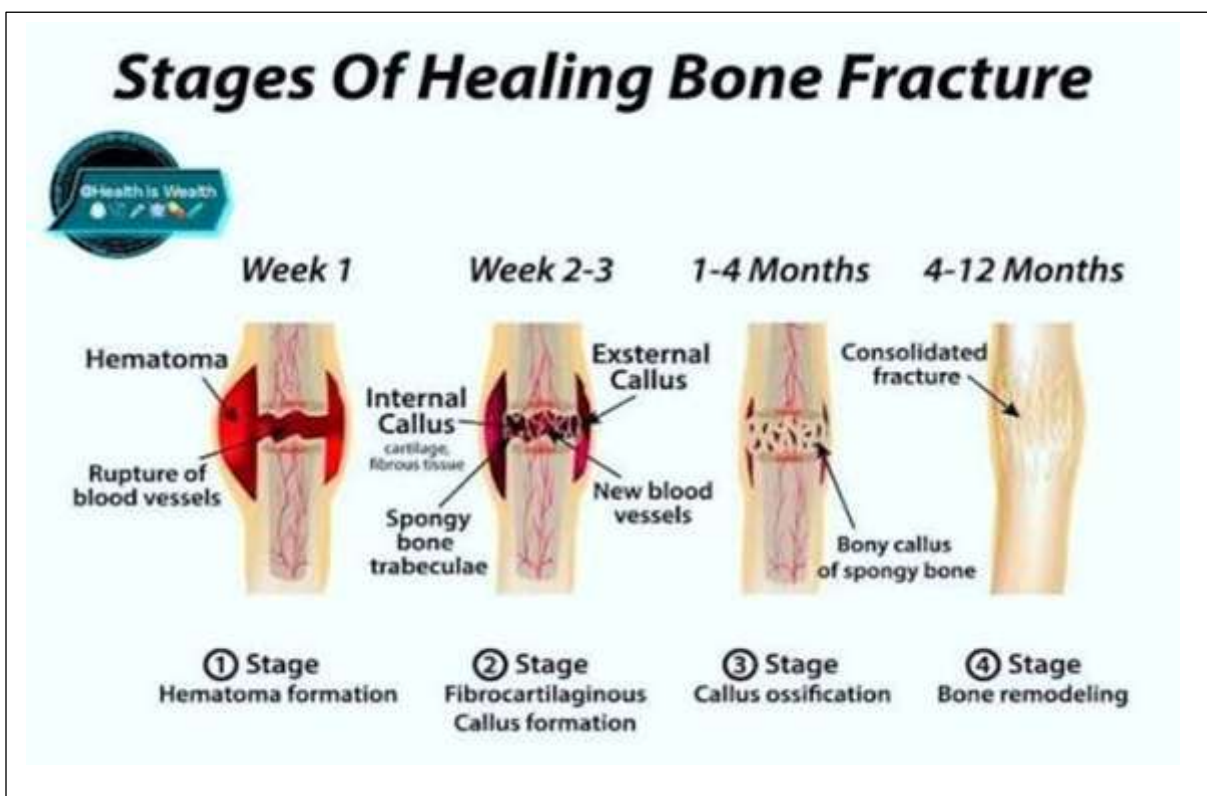


Figure 1: Stages of bone healing showing hematoma formation, fibrocartilaginous callus formation, callus ossification, and bone remodeling.

A. Autogenous Bone Grafts (Autografts)

The use of autogenous bone grafts is considered ideal for bone grafting because of their biological characteristics; these grafts are formed from the patient's own bone and are harvested from the patient's mouth or other areas of the body. There is no risk of an immune system reaction or potential disease transmission.

Biological Properties: These grafts are the most successful because of the participation of osteogenic cells, bone morphogenetic proteins, and additional supporting structures, providing osteoinduction and osteoconduction. The grafts contain an organic matrix made from collagen and non-collagenous proteins which promote the recruitment and differentiation of osteoblasts.

Donor Sites: The most common intraoral donor sites are the anterior mandible's symphysis, the body of the posterior mandible, and tuberosity, which make bone donation easy and painless. The most commonly used extraoral bone sites are the iliac crest, cranial top, the shin bone, and the fibula, which contain a lot of bone for suprastructural grafting.

Some studies showed that grafts from the mandible symphysis and grafts from the iliac crest for repairing an alveolar cleft have the same amount of bone. The iliac crest grafts have longer surgery times and more operational complications [7].

Volumetric Stability: Predictable results for implant placement show that autogenous mandibular body block grafts maintain volumetric stability with an average residual bone of $74.6 \pm 8.4\%$ after resorption [8].

Source and Harvesting: Donor sites for autografts, and their anatomy, Grafts from the lateral tibia are low risk, and yield a good quantity of cancellous bone, making them preferable to other sites [6].

Bone graft materials are commonly classified according to their biological origin into four main categories: autografts, allografts, xenografts, and alloplastic grafts, as shown in Figure 2.

CLASSIFICATION OF THE BONE GRAFTING MATERIALS			
Autogenous Bone Bone from same individual	Allogenic Bone Bone from same species from another individual	Xenogenic Bone Material of biologic origin but from another species	Alloplastic Bone Material of synthetic origin
Block graft	Free frozen bone	Material derived from animal bone	Calcium phosphates
Bone mill Bone scraper Suction device Piezo Surgery	Freeze-dried bone allograft	Material derived from corals	Glass ceramics
	Demineralized freeze-dried bone allograft	Material derived from calcifying algae	Polymers

Figure 2: Classification and Biological Properties - Hierarchical classification of all bone graft material types with their biological characteristics.

B. Allogenic Bone Grafts (Allografts)

Allogenic bone grafts are sourced from humanitarian cadaveric donors, carefully processed, and preserved to minimize immunogenicity and to maintain biological activity. These materials offer excellent availability and remove the concerns of donor site morbidity.

Biological Properties: Allografts primarily act through osteoconduction, and processed appropriately, can also act through osteoinduction. Demineralized bone

matrices of allogeneic origin, enhance the osteoinduction properties due to the retention of organic constituents such as, growth factors, and Bone Morphogenetic Proteins (BMPs). Biological performance is influenced by freeze drying, demineralization and gamma irradiation processing [9].

Clinical Applications: Similar to some autogenous bone grafts in their regenerative capability to critical size defects, partially demineralized allogeneic bone paste demonstrates comparable new bone formation and graft integration [2]. In various combined bone allogeneic with scaffolds, osseointegrative properties have been confirmed in several clinical situations.

Effectiveness: Allogeneic bone Ashby et al. (2023) analyzed the regenerative effect and new bone formation of fresh frozen bone allografts and concluded, though autografts had better overall bone composition and tissue incorporation, the regenerative capacities and new bone formation percentages were comparable [10].

Safety Considerations: Contemporary rigorous screening, testing for infectious diseases (HIV, hepatitis C, syphilis), and processing protocols have minimized transmission risks. However, careful material selection and monitoring remain essential.

C. Xenogeneic Bone Grafts (Xenografts)

Xenogeneic bone grafts come from non-human species, mainly from bovines and porcine sources. These materials are widely recognized in clinics due to their availability, reliability and proven adaptability to various forms of regenerative medicine.

Biological Properties: The biological xenografts have osteoconductive property due to the minerals present in them (i.e., hydroxyapatite and collagen) which enables cellular infiltration and bone apposition. Immunogenic cellular elements

are removed via decellularisation and in this process structural elements and bioactive molecules are preserved [11].

Material Composition: The major components of xenografts are the minerals which are inorganic in nature (which include calcium phosphates and hydroxyapatite) and collagen which is an organic component. The processes which include deproteinization, demineralization, and sterilization affect the osteoconductive and osteoinductive potentials of the xenografts. Excellent biocompatibility and volumetric stability are characteristic for bovine-derived materials. [12]

Comparative Effectiveness: When studying porcine versus bovine xenografts and autogenous bone, the same parameters of bone formation and clinical outcomes were achieved in sinus floor augmentation [13]. For implant survival and aesthetics, collagenated xenogeneic bone blocks were clinically as good as the autogenous bone blocks [14].

Integration and Resorption: In comparison to autografts, xenografts have a slower resorption time, often having some residual components after 6-12 months in multiple studies. This resorption pattern can be beneficial when trying to maintain the volume of the augmented areas [15].

D. Alloplastic (Synthetic) Bone Grafts

Synthetic bone graft materials provide regulated biodegradation, osteoconductivity, and mechanical strength, and are designed to replicate the attributes of natural bone.

Types of materials: The principal type of alloplastic materials consists of:

- Bone Cement

- Calcium sulfate
- Bioactive Glass
- Composite materials (polylactic acid, polycaprolactone)
- Injectable biocompatible materials (bone cements and pastes)

Biological Properties: The alloplastic materials mainly operate via biocompatibility, and provide structural frameworks for cellular infiltration and the development of new bone through osteoconduction. Their unique attributes of crystallinity motivate specific cellular responses and protein binding [1].

Advantages and Limitations: Synthetic biomaterials are widely available, possess uniform characteristics, and have predictable breakdown with no risk of disease transmission. Many synthetic biomaterials, however, still do not have the property of osteoinductivity, and some of them may have excessive resorption, linger on-site, or have other resorption products, which may be a risk to long-term stability [3].

Clinical Efficacy: Beta-tricalcium phosphate and biphasic calcium phosphate have been shown to be clinically effective, with comparable results to autografts and xenografts in many instances, having successful bone formation and integration with the implant. A network meta-analysis of randomized controlled trials showed that autografts achieved 12.33% more new bone formation than biphasic calcium phosphate,

IV. CLINICAL APPLICATIONS

Bone grafts serve diverse clinical functions in oral and maxillofacial surgery, with material selection and technique determined by specific clinical requirements, defect characteristics, and patient factors.

A. Development of Sites for Dental Implants

Successful osseointegration of dental implants requires certain parameters including the bone volume and density, as well as the anatomical placement. Many patients experience some degree of alveolar bone deficiency requiring augmentation procedures.

Ridge Augmentation: Guided bone regeneration (GBR) involves the use of a barrier membrane along with a bone graft material for the enhancement and preservation of the bone volume at the implant site. Autogenous bone graft studies with horizontal ridge augmentation have proven to yield better results with 1:1 combinations of autograft and xenograft than with xenograft alone, although the results were not statistically significant [17].

Sinus Augmentation: Among the numerous augmentation procedures done, maxillary sinus floor elevation also referred to as sinus lift, is one of the most common. Many different types of grafting materials have been employed successfully. The lateral bone window combined with particulate grafts achieved 96.7% of the cases with complete integration of the bone lid [18].

Immediate Implant Placement: In the case of immediate implant placement after a tooth is extracted, is successful osseointegration and soft tissue healing, Platelet-rich fibrin (PRF) is of great value as evidenced following the extraction of a molar tooth, and the application of PRF with the immediate implant [19].

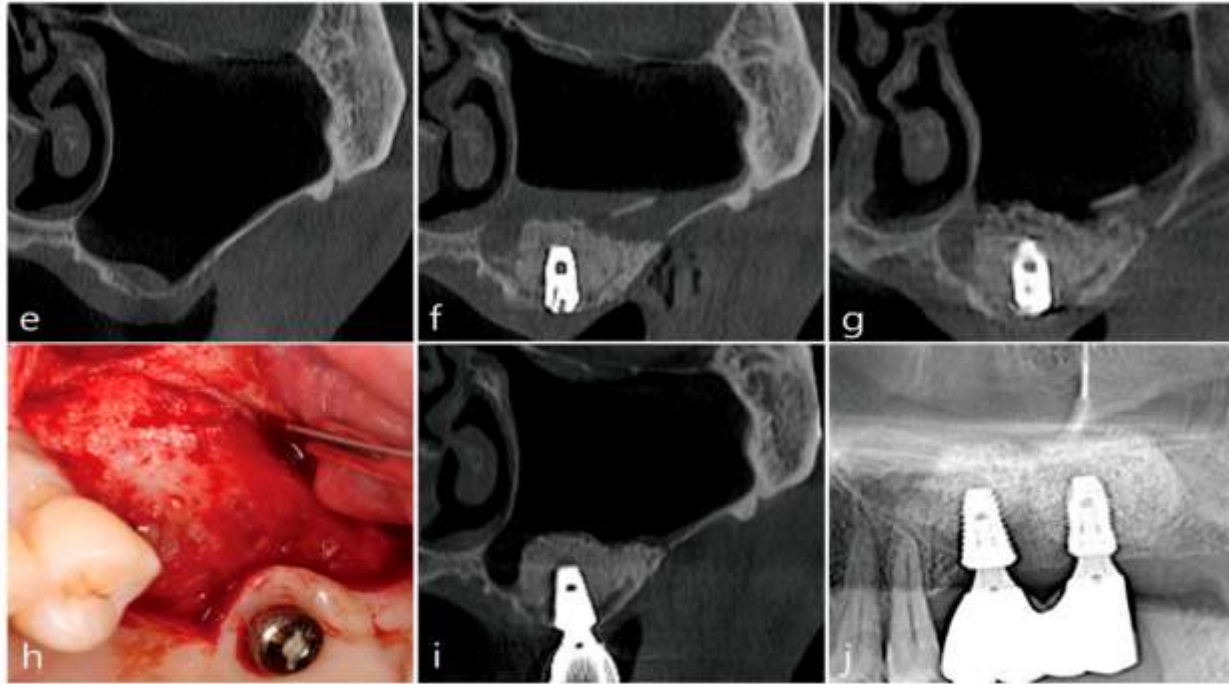


Figure 3: Maxillary Sinus Augmentation Using Xenograft Material

B. Trauma and Reconstruction Following Tumor Resection

Mandibular continuity deficits caused by trauma, tumor removal, or other surgical ablation, must be reconstructed using bone grafts to restore functionality and aesthetics.

Vascularized fibula bone grafts: vascularized fibula bone grafts are, and probably will be, the benchmark for extensive mandibular reconstructions, especially after tumor resections. A systematic review of vascularized fibula bone grafts and mandibular implants described graft survival at 98% and implant survival at 92.6% [20]. Success rates were comparable for primary and secondary implants.

Non-vascularized bone grafts: iliac crest non-vascularized bone grafts can also be used for the reconstruction of mandibles, especially in resource poor areas. Most of 20 patients reconstructed with iliac crest grafts after mandibular resection, maintained bone stability and good facial profile maintenance, throughout 1 year of follow up [21].

Customized Reconstruction Approaches: 3D printing and computer-aided design have the ability to create customized titanium meshes for mandibular reconstruction. Along with particulate cancellous bone and marrow grafts, these techniques offer better control of volume and improvement in anatomical accuracy [22].

C. Alveolar Cleft Reconstruction

This standard surgical procedure, performed between orthodontic stages, aims to stabilize the cleft-adjacent dentition and assist in the scheduled eruption.

Outcomes and Timing: Closing adjunctive orthodontic spaces after early secondary alveolar bone grafting, and based on the mineralization stages of the canines, showed improved and preserved graft outcomes [23]. The combination of symphysis bone grafts and allograft, in relation to donor site morbidity, is improved allograft outcomes to iliac crest grafts [7].

D. Congenital Abnormalities and Developmental Defects

Congenital bone defects, including micrognathia, maxillary hypoplasia, and other developmental anomalies, often demand bone grafting to aid in functional and aesthetic reconstruction in children and young adults.

Multidisciplinary Approach: Surgical repair of cleft lip and palate, along with use of vascularized fibula grafts and implants, shows adequate results in the long

term [24]. Collaborative cross-disciplinary surgical, orthodontic, and prosthetic planning and rehabilitation maximizes final results.

The following clinical case demonstrates the effect of Platelet-Rich Fibrin (PRF) in enhancing soft tissue healing and bone regeneration following dental procedures.



Figure 4: Clinical application of PRF in soft tissue healing after dental procedure

This figure shows the progressive healing of the surgical site following PRF application. A noticeable improvement in tissue regeneration and wound closure can be observed over time, highlighting the effectiveness of PRF in clinical practice.

V. EFFECTIVENESS EVALUATION

Assessment of bone graft effectiveness requires comprehensive evaluation across multiple outcome parameters spanning immediate postoperative period through long-term follow-up.

A. Bone Volume Stability and Architectural Outcomes

The ability to maintain augmented bone volume is an important indicator of the effectiveness of a graft. Radiographic evaluation through cone-beam computed tomography (CBCT) allows for accurate measurement of graft volume.

Results of Ridge Augmentation: Using a combination of autografts and xenografts for alveolar ridge augmentation resulted in a mean vertical gain of 2.09 mm and a mean horizontal gain of 0.99 mm, which were both sustained at the 6 month post-operative evaluation [17]. In comparative studies, the sites treated with allografts incurred a lower risk of bone loss than the uncrossed control sites [25].

Volume Preservation: When combined with autogenous bone, xenograft materials demonstrate an excellent ability to preserve volume. In a study, porcine-derived xenografts combined with autogenous bone resulted in a mean vertical bone gain of 5.87 mm and 5.31 mm with bovine-derived xenografts, and there were significant differences in the mean horizontal bone gain [12].

Residual Material Considerations: The visible graft residues in histology at the time of implant placement, which range from 4.14% for xenografts to 26.2% for alloplastic materials, indicate potentially different patterns of resorption that may impact long term stability [15].

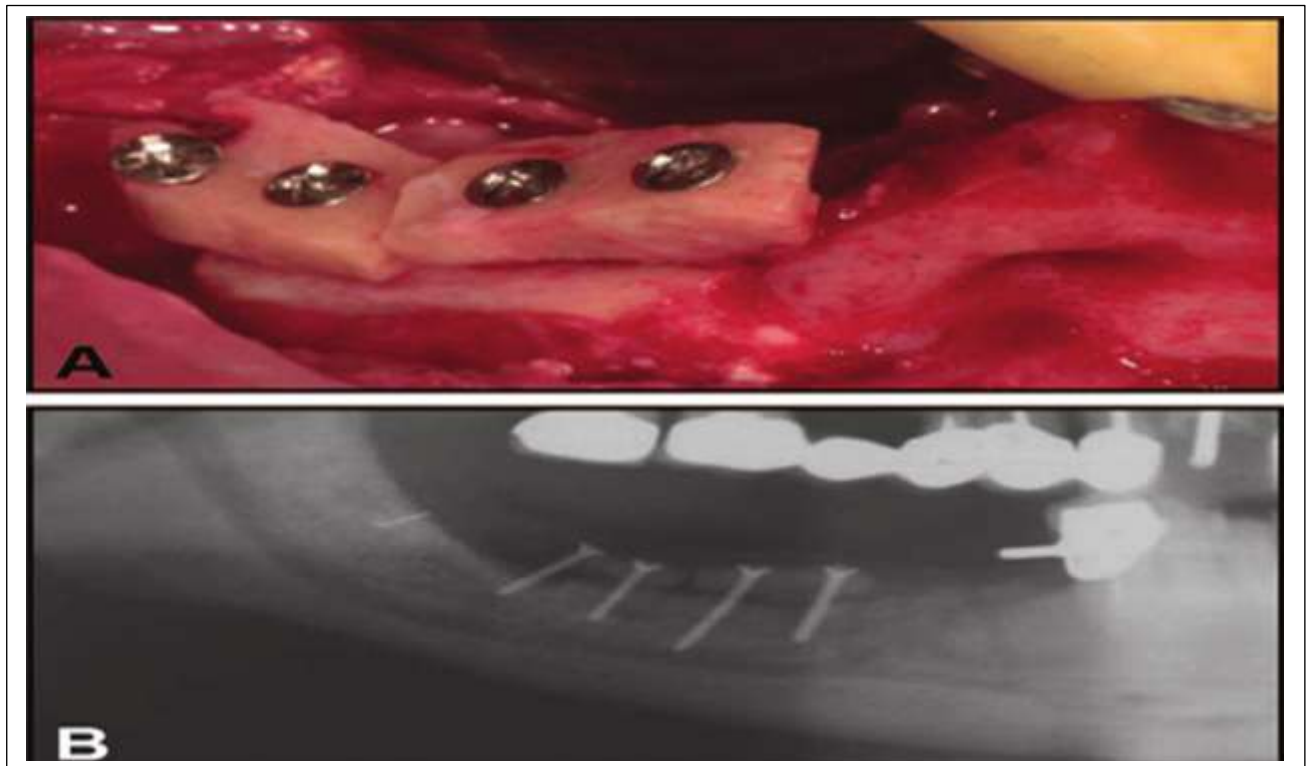


Figure 5: Autogenous Mandibular Block Graft for Ridge Augmentation

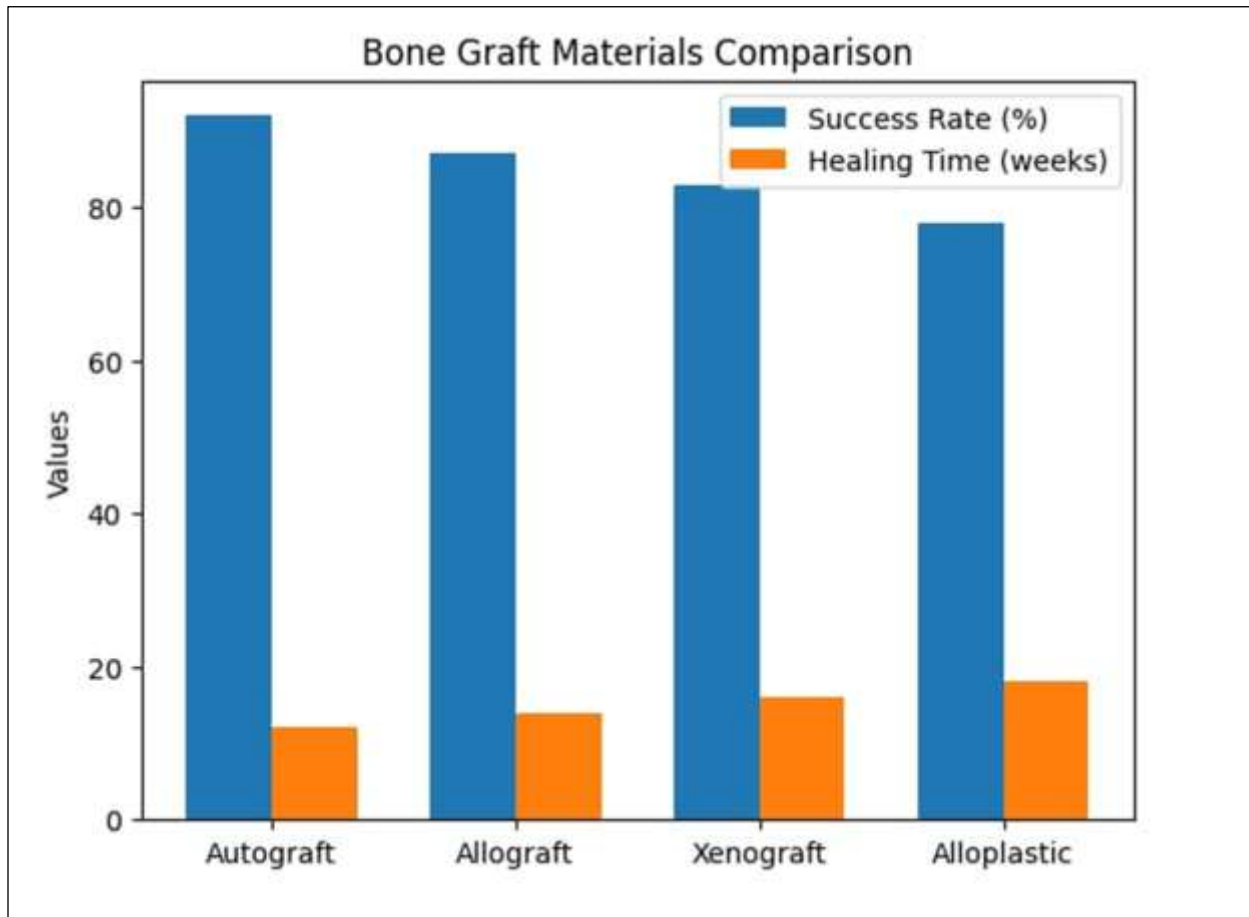


Figure 6: Comparison of success rates (%) and healing time (weeks) among different bone graft materials.

B. Osseointegration and Implant Stability

Evaluating osseointegration of an implant provides the most basic measure of the graft's effectiveness in implant applications. Assessment of primary and secondary implant stabilities serve as objective indicators of bone quality and its integration.

Implant Survival Rates: Meta-analysis of implants in augmented bone showed comparable survival rates irrespective of the type of augmentation [26]. Long-term studies with a mean follow-up of 6 years demonstrated sustained success rates across all three techniques: GBR, ridge split, and onlay grafting.

Marginal Bone Loss: Changes in marginal bone levels after the implants were loaded showed an average of 0.5-0.57 mm at 24 months, with no significant difference among the groups of autograft, allograft and xenograft at follow-up [27]. These losses were within the acceptable range and were not statistically different in the type of graft.

Primary Stability: The combination of Advanced Platelet Rich Fibrin (A-PRF) and xenografts resulted in higher implant insertion torque, and primary and secondary stability compared to the controls [28].

C. Bone Regeneration Quality and Maturation

The evaluation of histology and histomorphometry gives us a greater understanding of the quality of the incorporated graft and the regeneration of the bone.

The Formation of New Bone: Quantitative histomorphometric analyses showed that the highest percentages of new vital bone formation were associated with the melt autogenous bone grafts. Autograft specimens had a statistically significantly larger bone marrow area [29].

Timelines of Healing: The patterns of new bone formation are sequential and predictable. The new progressive formation of bone and integration of the graft were captured in the histological analyses of the time intervals which showed complete maturation of bone by 12 weeks [29].

Contact of Graft and Bone: The percentage of bone formation contact between the graft material and newly formed bone impacts a lot the the long-term stability. The same contact percentages were observed in the PRF and non PRF studied groups [30].

D. Long-Term Success Rates and Stability

Long-term studies track the effectiveness of Graft and the life span of implants.

Implant Success in Reconstructed Sites: When extraoral autogenous bone grafts are used, the recorded long-term survival and success rates of the implants are 94.9% (CI: 90.1%-97.4%). Non-vascularized iliac grafts survived 96.5% (CI: 91.4%-98.6%); Non-vascularized calvaria grafts survived 92.3% (CI: 89.1%-94.6%). These are based on almost 92 months of follow-up [31].

Stability of Marginal Bone Loss: Illustrating bone stability, the mean marginal bone loss (MBL) was 2.25 mm (iliac graft), 0.93 mm (calvaria graft), and 1.49 mm (fibula graft) at the long-term follow-up.

VI. FACTORS AFFECTING OUTCOMES

Multiple interconnected factors significantly influence graft success and clinical outcomes. Understanding these variables enables optimization of patient selection, material choice, and surgical technique.

A. Patient-Related Factors

Age and Bone Quality: Older age and lower bone quality have negative impacts on graft success. More stagnant/inactive bone remodeling due to age, decreased osteogenic cell activity, and changes to the inflammatory cascade all lead to decreased bone healing. While studies show that iliac crest complications seem to be the same regardless of age, younger and older, careful medical optimization is still very much recommended [32].

Systemic Health Status: The presence of systemic diseases like diabetes, autoimmune disorders, and conditions of immunosuppression are caused by disrupted systemic disease and is bone healing and graft incorporation. While the implant and bone guides are regenerated, the immunocompromised patients show the feasibility of the techniques, and therefore the close surgical procedure and the careful postoperative will be the most important [33].

Smoking and Lifestyle Factors: The factors of lifestyle are smoking. Smoking impacts bone healing through several ways, including less blood flow and changes to the inflammatory cascade. In the case of Advanced ARF, patients who have never smoked demonstrated greater clinical advancements compared with smokers, although all patients showed a positive clinical result regardless of smoking status [34].

Prior Irradiation: Patients with prior head and neck radiation demonstrated reduced implant survival in vascularized fibula bone grafts compared to non-irradiated patients, though differences did not consistently reach statistical significance in all studies [20].

B. Surgical Technique Considerations

Graft Placement and Stability: Primary surgical techniques improve the integration and osseointegration of grafts. Negligible primary stability, graft contamination, and improper positioning compromise outcomes. Using Tenting pole abutment and GBR (Guided Bone Regeneration), seems to be a safe and effective approach for advanced ridge augmentation [35].

Barrier Membrane Selection: Various factors such as porosity, degradation rate, and the mechanical properties of barrier membranes, all affect the rate of bone regeneration. While resorbable collagen membranes offer biological integration, non-resorbable titanium mesh provides better space maintenance. Predictability is enhanced with customized membranes made from advanced techniques [36].

Timing of Implant Placement: The choice of delayed and simultaneous implant placement is a critical technical consideration. Early simultaneous implant placement using PRF (Platelet Rich Fibrin) has shown good outcomes; however, delayed protocols are typically 4–6 months of healing prior to the insertion of the implant for bone maturation [4].

C. Material Properties and Composition

Surface Characteristics: The roughness, porosity, and chemical composition of the graft material have significant effects on cellular behavior, protein adhesion, and osseointegration. Surface alterations on the microscale and nanoscale improve the response of osteogenesis and the differentiation of cells [5].

Mechanical Properties: The compressive strength and elasticity of the graft material must be in accordance with the requirements of the recipient site. Scaffolds with comparable mechanical properties to the native bone tend to have increased biological activity and integration [37].

Degradation Profile: The rate of material degradation must ensure the preservation of the structural support as the material is gradually supplanted by the newly formed bone. If the degradation is too rapid the structural integrity is compromised, whereas too slow degradation may inhibit complete bone formation and remodeling [3].

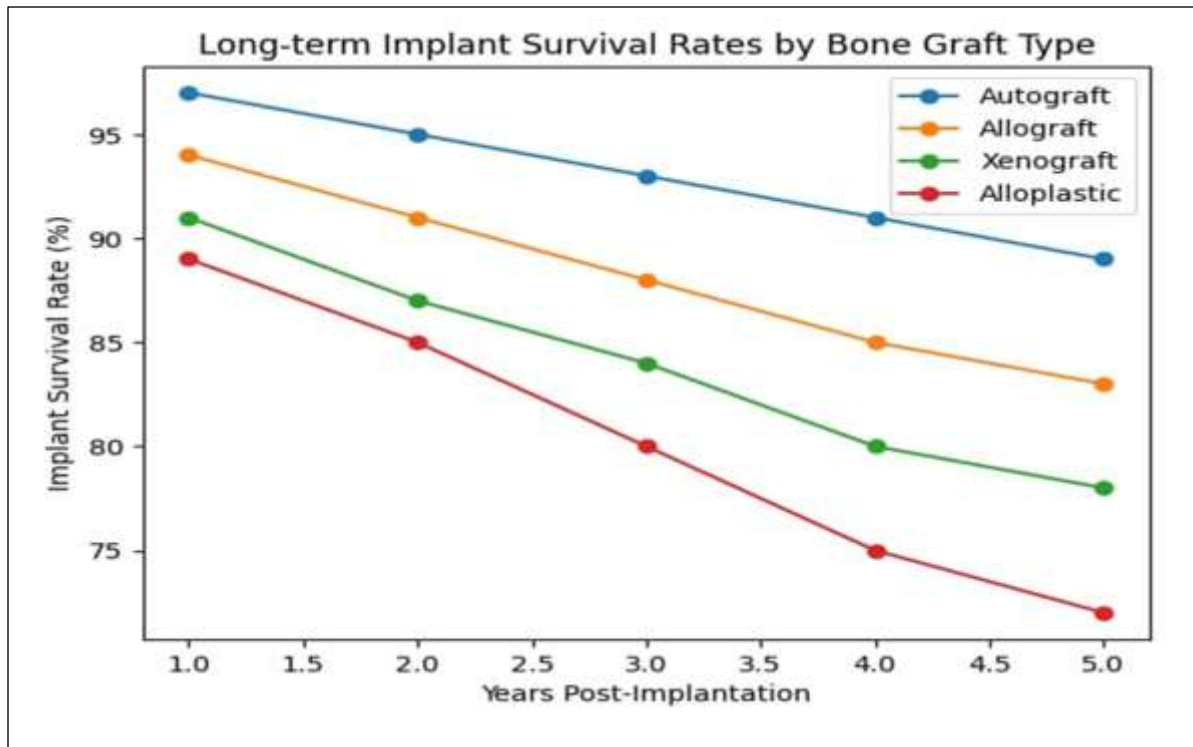


Figure 7: Long-term implant survival rates over 5 years for different bone graft materials

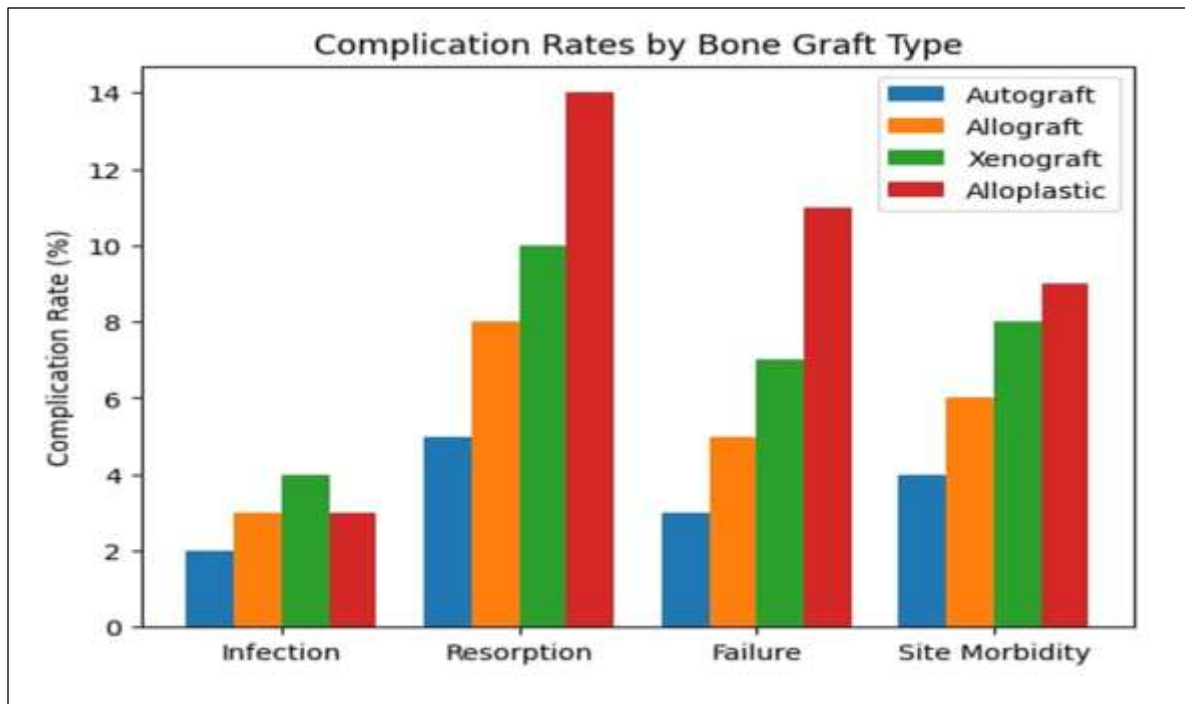


Figure 8: Comparison of complication rates among different bone graft materials

VII. COMPLICATIONS

Bone grafting procedures, while generally safe, carry inherent risks and potential complications affecting both donor and recipient sites.

A. Infection

Occurrence and Contributing Factors: The most frequent complication of bone grafting procedures are surgical site infections. A substantial number of patients experienced recipient surgical site infections (RSSI) after the vascularized fibular bone grafting procedure. American Society of Anesthesiologists (ASA) physical status class and contamination of the operative field were considered to be the most significant of the numerous documented risk factors [38].

Infection control: The risks of infection are reduced when primary closure is performed with tension free adaptation of the wound followed by the closure of the field, and by the application of a surgical technique that is methodical. The selection of patients and the optimization of their systemic condition will further reduce the risks of infection.

Bone loss is a common consequence following tooth extraction, particularly in the absence of appropriate intervention. The alveolar bone begins to resorb rapidly, leading to a reduction in both width and height of the bone. This resorption may compromise future dental procedures, especially implant placement, by reducing bone stability and support.

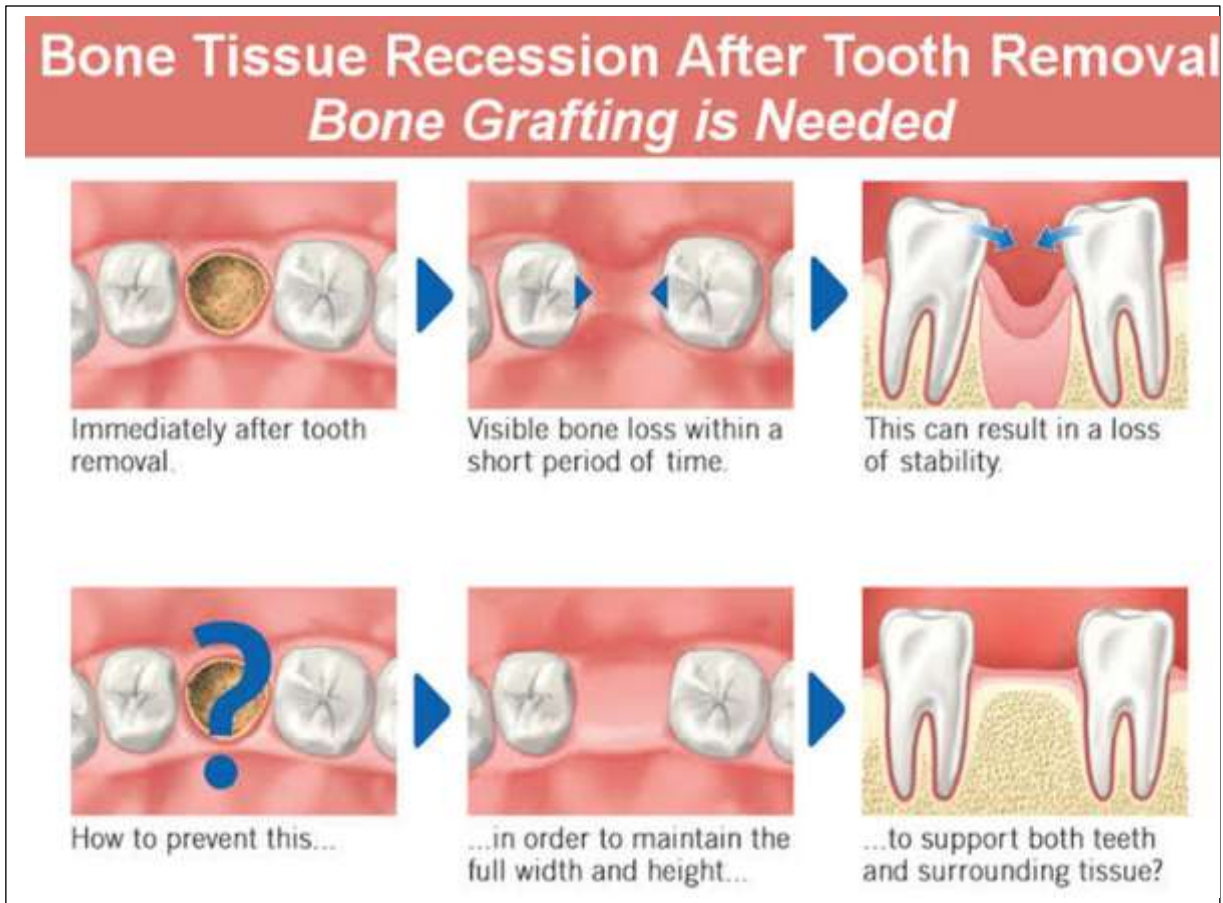


Figure 9: Bone Loss After Tooth Extraction and the Role of Bone Grafting

As shown in the figure, bone resorption begins shortly after tooth extraction, leading to a gradual loss of alveolar bone volume. This reduction can negatively affect the stability and success of future dental implants. Therefore, bone grafting is essential to preserve bone structure and maintain adequate support for restorative procedures.

B. Graft Failure

Total Failure: Total graft failure happens when there is a lack of bone growth needed to fill the space for the implant. While this complication is rare with current practices, it requires either revision grafting or other procedures.

Partial Resorption: When the graft is excessively resorbed, the implant cannot be placed, or is compromised in its stability. Factors contributing to this include, mechanical issues, infection, poor blood flow, or the properties of the grafting material.

Prevention Strategies: Several methods have been shown to lower the risk of resorption, such as using more cortical bone, better protected barrier membranes, use of growth factor, and modified recipient bed preparation [25].

C. Donor Site Morbidity

Iliac Crest Harvesting: Bone grafting at the iliac crest is linked to moderate donor site morbidity, though the degree of morbidity is less than what has historically been described. Postoperative complications may include chronic pain, paresthesia, scarring, and alterations in gait. Most complications are mild and of short duration [39].

Considerations with Elderly Patients: Harvesting of iliac crest in elderly patients showed similar complication rates compared to younger patients. There were also no significant differences in terms of disruption, formation of hernias, bone fractures, or issues with healing of the wounds [32].

Tibial Harvesting: Tibial graft harvesting by the medial approach is more favorable compared to the lateral approach, with shorter operating times, few complications, and an easy recovery with no gait disturbances [6].

Intraoral Harvesting: Grafts of the symphysis and body exhibit low morbidity, with complications limited to a superficial infection, pain, and suture dehiscence, all of which resolved without functional impairment [6].

VIII. ADJUNCTIVE THERAPIES

Innovative methods in regenerative medicine are incorporating traditional bone graft materials with biologically active substances that drive osteogenic response. these bone graft enhancers will produce positive reaction on osteogenesis, tissue integration, and angiogenesis through a multitude of different molecular pathways.

A. Platelet-Rich Fibrin (PRF)

PRF is classified as a second-generation thrombin free platelet concentrate (no additives), that is obtained through the centrifugation of whole blood. PRF serves as an osteoconductive matrix that supports the reassurance of bone.

Biological Properties: The composition of PRF is described as an autologous conglomerate of platelets, leukocytes, and a plasma fibrin matrix which is rich in a variety of sequestered and unactivated growth factors including PDGF, TGF- β , VEGF, and bFGF [40]. The fibrin matrix is a demonstrative component of the PRF that produces, and prolongs the assimilation of bioactive molecules for approximately 10-14 days. This assists in the angiogenesis and cellular proliferation and differentiation. [41]

Clinical Efficiency: Systematic surveys showed PRF positively influenced healing in various applications. Socket preservation with PRF resulted in less vertical bone loss when compared to control groups. PRF treated groups had lower incidence rates of osteo alveolar dry sockets. There were gain in clinical attachment levels in the regeneration of periodontium [42].

Formulations and Modifications: PRF variants such as Advanced PRF Plus (A-PRF+), Leucocyte-PRF (L-PRF), and injectable PRF (i-PRF) exhibit more refined characteristics. When compared to other PRF products, A-PRF+ displayed superior

results in hard tissue applications with more as well as less vascularized bone and fewer connective tissue inclusions [43].

Cost-Effectiveness: Producing PRF can be done with little more than a chair-side cost of \$50-100 per patient. Producing a patient specific PRF prototype is a cost saving, adjunctive therapy when compared to expensive growth factor treatments [41].

B. Bone Morphogenetic Proteins (BMPs)

BMPs are a type of naturally occurring signaling molecule. These molecules can trigger the differentiation of stem cells into bone forming cells (ossification) by interacting with the serine/threonine kinase receptors.

Mechanism of Action: BMPs, such as the BMP-2, BMP-7, and other Bone Morphogenetic Proteins, influence intracellular signaling pathways with the potential for the Smad protein signaling. These pathways gets activated, causing an increase in the expression of the transcription factors that are responsible for osteogenesis. Subsequently, this leads to the differentiation of stem cells into cells of the osteoblast lineage.

Clinical Efficacy: Bone regeneration and improvement of implant stability within four months was achieved with the use of rhBMP-2 and 3D titanium mesh bone scaffolds and xeno/allograft scaffolds. In the case of treatment of cervical radiculopathy, BMP-2 was highly probable in reducing the pain and improving functionality.

Safety BMPs: in the management of cervical radiculopathy, pose a probable risk of vertebral fracture. BMPs are the most expensive of the biological adjuncts, which makes it a challenge to use them in the day to day clinical practice. Each region have different rules and guidelines about the use and approval of BMPs.

C. Other Adjunctive Approaches

Concentrates of Growth Factors (CGF): Concentrated Growth Factors, obtained through the specialized centrifugation process, show similar clinical handling characteristic improvements as the regenerative property of PRF.

Demineralized Bone Matrix: The processed allogeneic bone still retains some of the osteoinductive properties due to the non-collagenous proteins and growth factors, which offer synergistic benefits when combined with graft materials [47].

Mesenchymal Stem Cells: umbilical cord-derived mesenchymal stem cells combined with scaffolds and growth factors show promising bone regeneration in preclinical models and are beginning to have real world clinical evidence in [45]

The use of platelet-rich fibrin (PRF) in combination with bone graft materials has gained significant attention in oral and maxillofacial surgery due to its regenerative potential. PRF is a natural biomaterial rich in growth factors that enhance tissue healing and bone regeneration. When mixed with bone graft granules, it forms a cohesive material known as “sticky bone,” which improves graft stability and handling during surgical procedures. This approach not only facilitates the placement of the graft but also enhances biological activity at the site, promoting faster healing and better clinical outcomes.

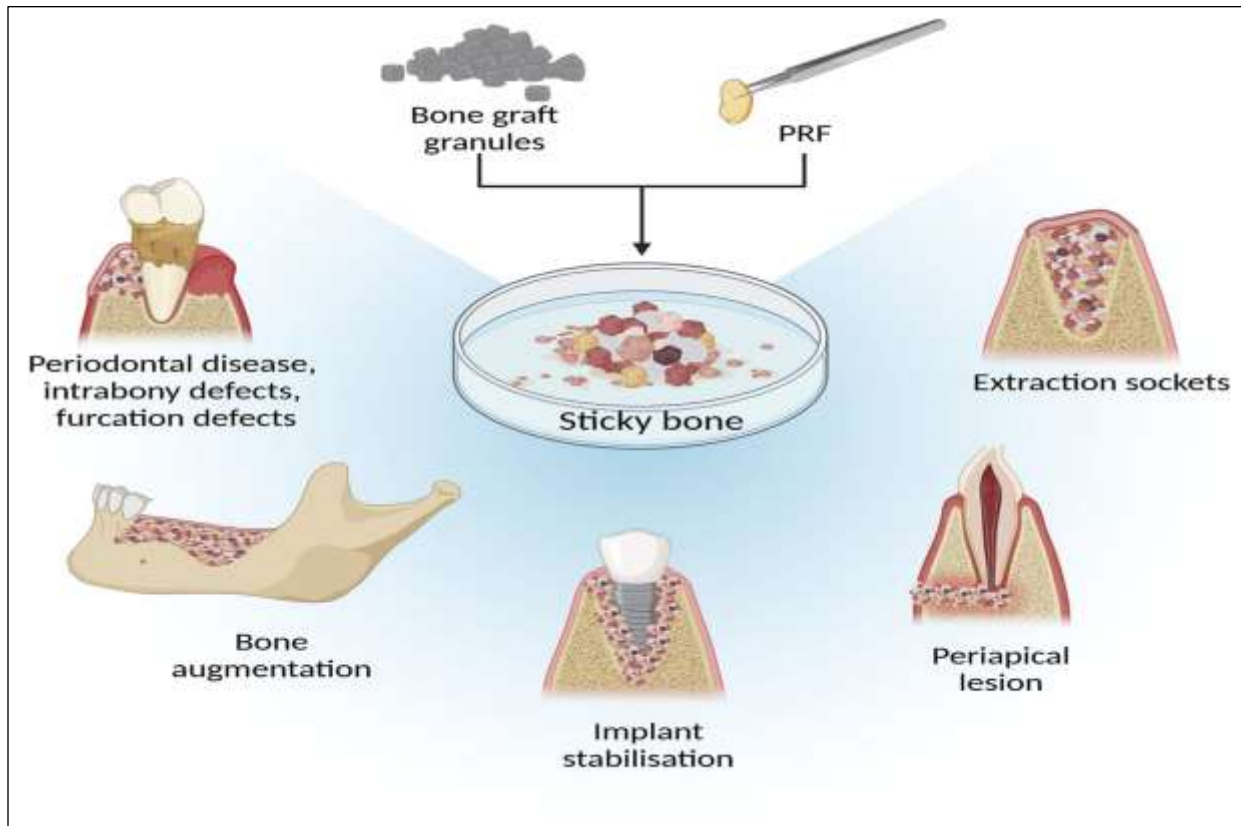


Figure 10: Preparation and Clinical Applications of Sticky Bone Using PRF and Bone Graft

The figure illustrates the preparation of sticky bone by combining bone graft granules with platelet-rich fibrin (PRF). This combination improves the handling and stability of the graft material during surgical procedures. Additionally, PRF releases growth factors that enhance bone regeneration, promote angiogenesis, and accelerate tissue healing. Sticky bone is widely used in clinical applications such as implant stabilization, bone augmentation, and treatment of extraction sockets and periodontal defects.

IX.ADVANCED TECHNOLOGIES

Innovations in regenerative medicine and bone healing technologies now adopt more personalized techniques.

A. Technologies in CAD/CAM and 3D Printing One of the technologies in 3D printing is the ability to create individualized bone scaffolds that are tailored to the precise design and architecture (including porosity and its bioactive components).

Recent advancements in digital technologies, particularly computer-aided design and manufacturing (CAD/CAM) and 3D printing, have significantly transformed the field of oral and maxillofacial surgery. These technologies enable the creation of highly precise and individualized bone scaffolds that are specifically tailored to match the patient's anatomical structure. By utilizing imaging techniques such as cone beam computed tomography (CBCT), accurate three-dimensional models of the defect area can be obtained and used for virtual planning.

Furthermore, computational optimization allows for the design of scaffolds with controlled porosity and mechanical strength, which are essential for promoting cell migration, vascularization, and new bone formation. The integration of bioactive materials and growth factors within these scaffolds further enhances their osteoconductive and regenerative properties.

As illustrated in Figure 9, the workflow involves several steps including virtual planning, computational design, fabrication using 3D printing technologies, and finally the surgical placement of the customized implant. This approach improves surgical precision, reduces operative time, and enhances overall clinical outcomes.

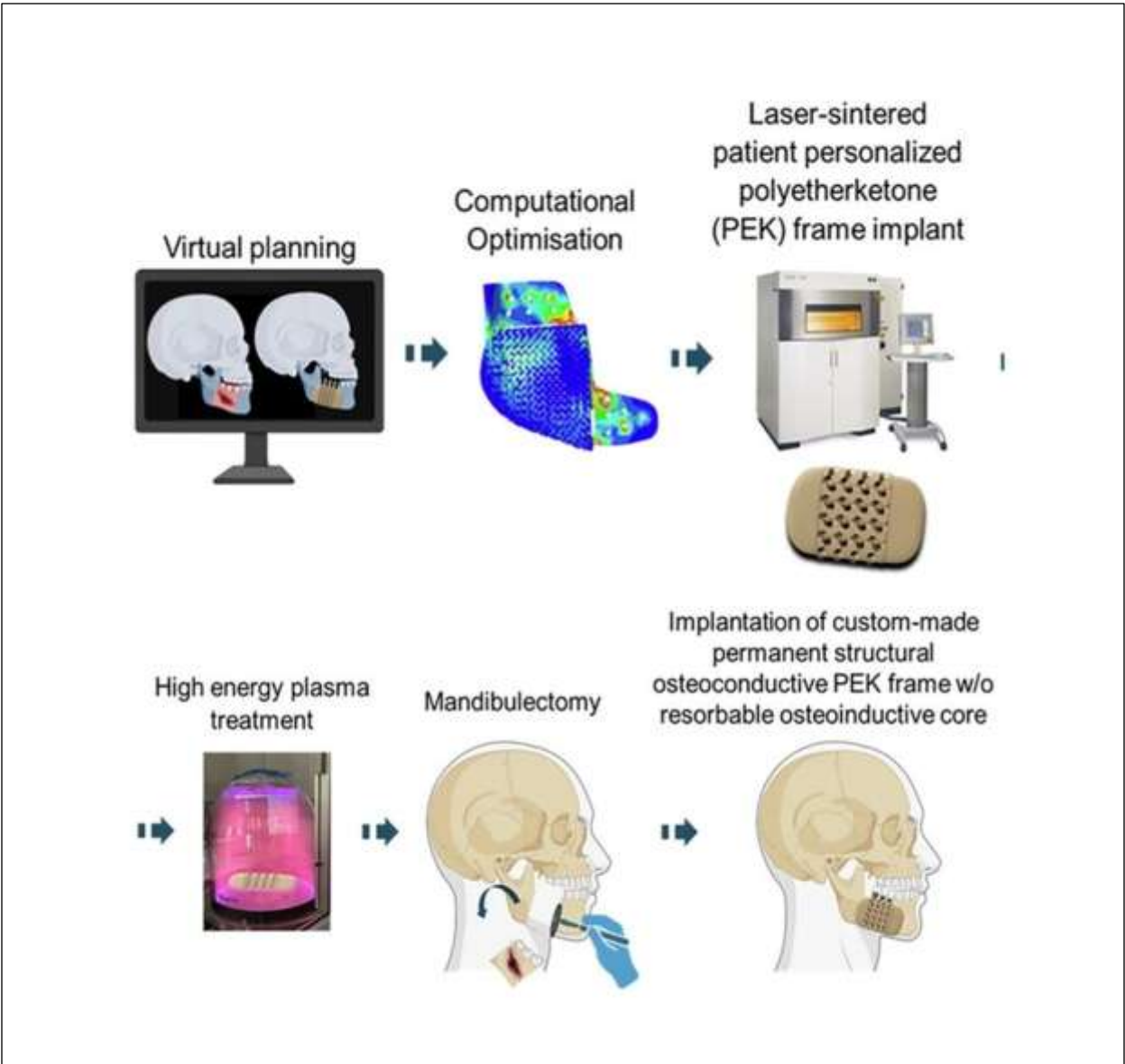


Figure11: Workflow of Customized 3D-Printed Implant for Mandibular Reconstruction

The figure shows the workflow of customized 3D-printed implant fabrication for mandibular reconstruction

Technical Capabilities. Preoperative planning and scaffolds design customization are achieved through DLP (digital light processing), FDM (fused deposition modeling), SLA (stereolithography), and/or other 3D printing techniques that allow stepwise construction, imaging, and precise geometry fabrication for surgical planning based on CT (computed tomography) defect analysis [47].

Scaffold Design Principles. An ideal scaffold balances porosity, with the framework of the scaffold over 70 percent porosity, and the architecture of the pores is interlinked to allow for the diffusion of nutrients, ingress of cells, and the formation of blood vessels (vascularization). Additionally, the scaffold must have a balanced, mechanical property that is structurally sound, along with a reasonable rate of degradation to the scaffold.

Materials: Primary materials for printing include polycaprolactone (PCL), polylactic acid (PLA), polyglycolic acid (PLGA), bioactive glass, hydroxyapatite, and certain composite formulations. While bioceramics provide osteoconductive features, biopolymers provide controlled degradation and mechanical tunability [41].

Clinical Applications: Customized titanium mesh fabrication for mandibular reconstruction allows accurate anatomical reconstruction with enhanced fixation and integration [42]. In combination with platelet-rich fibrin, three-dimensional printing resulted in successful guided tissue regeneration with a significant 3D fill in the bone at the treatment site [43].

Outcomes: Compared to conventional methods, 3D printed scaffolds showed remarkable biocompatibility, and also enhanced cell adhesion, proliferation, and osteogenic differentiation. Successful integration of the scaffolds and bone formation were achieved in long-term studies on animals [44].

B. Tissue Engineering Approaches

Tissue engineering fuses biological scaffolds, cell components, and growth factors to create functional bone tissues restoring lost bone structures and functions.

Scaffold Materials: Modern scaffolds of tissue engineering use a variety of raw materials including natural polymers (collagen, gelatin, alginate, chitosan), synthetic polymers, bio-ceramics, and composite materials. The choice of materials is based on the required mechanical properties and biological activity as well as the degradation kinetics.

Cellular Components: Mesenchymal stem cells sourced from bone marrow, adipose, and dental tissues show osteogenic ability when combined with scaffolds and growing factors [47].

Vascularization Strategies: For critical-sized bone defects to be successfully regenerated, they must be vascularized. The addition of pro-angiogenic factors (VEGF, FGF), along with other design elements aimed at encouraging neovascularization, improves regenerative potential [45].

Immunomodulation: More sophisticated scaffolds that use immunomodulatory components stimulate the polarization of M2 macrophages. This helps create a macro environment that fosters the regeneration of bone [46].

C. Stem Cell Therapies

Stem cells derived from bone marrow, fat tissue, and even dental tissue, show promising ability to aid in the engineering of new bone tissue.

Biological Properties: Mesenchymal stem cells have the capabilities to develop into multiple types of cells, including those of the osteoblast lineage. They also

have immunomodulatory effects and secrete various bioactive molecules through paracrine signaling [47].

Clinical Applications: When stem cells were used in conjunction with scaffolding materials and osteogenic growth factors in bone defect models, the process of bone regeneration was improved. Bone healing was enhanced by the mononuclear cells' ability to galvanically connect with other cells, which improved blood vessel formation (angiogenesis) and the formation of bone (osteogenesis) [44]. The bioactive microRNAs and proteins which stimulate bone formation (osteogenesis) and blood vessel formation (angiogenesis) also improved bone formation.

X. Clinical Indications for Bone Grafting and Sinus Lift

In many clinical cases, especially in the posterior maxilla, bone volume is insufficient for dental implant placement. Therefore, procedures such as bone grafting and sinus lift are performed to increase bone height and density. As shown in Figure 12, these techniques play a crucial role in creating a stable environment for implant placement and improving long-term clinical outcomes.

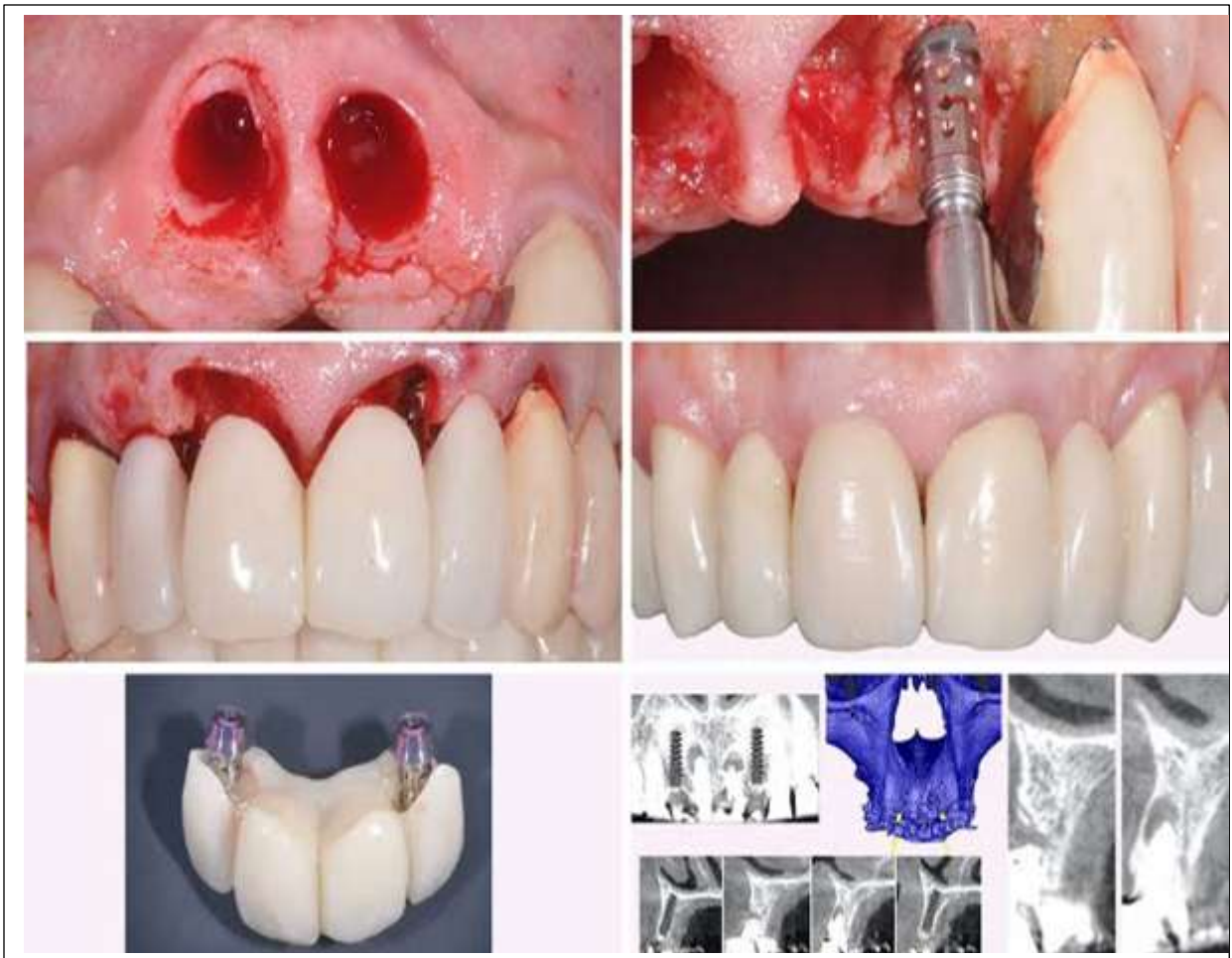


Figure 12: Bone grafting and sinus lift procedures prior to dental implant placement.

As shown in Figure 12, bone grafting and sinus lift procedures are performed to increase bone height and density in areas with insufficient bone volume, particularly in the posterior maxilla. These techniques create a stable and suitable environment for dental implant placement, thereby improving implant stability and long-term clinical success.

XI. CLINICAL GUIDELINES AND RECOMMENDATIONS

Evaluating important patient and defect characteristics along with the material properties is integral to effective, evidence-based clinical decision-making. This is important to streamline the clinical outcomes while balancing the costs.

A. Evidence-Based Material Selection

Defect Size and Complexity: Alloplastic materials, or combinations thereof, provide sufficient defect closure for small intraoral gaps. Moderate gaps may require the addition of an autograft or a xenograft. For large gaps and more complex intraoral conditions, autogenous bone and/or a vascularized flap is necessary [40].

Patient Factors: All patient types may be fine with all materials. However, for compromised patients, material selection is more restricted and is prioritized to those with high biocompatibility and fast incorporation. Patients with osteoradionecrosis may benefit more from an autogenous bone and/or a biological enhancement [33].

Anatomical Location: For maxillary anterior, even with all the tissues healed, the xenograft/anterior must be an autograft. A alloplastic may be more reasonable posteriorly. In the mandible, the bone is more supportive and may need to be an alloplastic. [4]

B. Treatment Algorithms and Clinical Pathways

Systematic decision-making incorporating patient optimization, appropriate material selection, and technique standardization optimizes outcomes and reduces complications.

XII. LIMITATIONS AND CHALLENGES

A. Research Gaps and Evidence Limitations

Study Design Heterogeneity: Methodological heterogeneity in studies makes it difficult to draw any direct conclusions. Differences in follow up timelines, outcome assessment, patient populations, and surgical techniques makes it difficult to complete meaningful meta-analyses in many studies [641].

Not All Evidence Gaps Have Been Filled: The synthesis of the literature on platelet concentrates regarding the lack of standard operating procedures on the techniques of preparation, application, and evaluation of the outcomes remains. More research will need to follow standardized procedures and have more extensive reporting [2].

Shortage of Data for Extended Time Frames: Many studies have data reporting on outcomes for up to 12 months, and very few have data for 3 to 5 years. Lasting stability, especially concerning the remaining materials and their patterns of resorption will require more data [31].

B. Ethical Considerations

Allograft Materials: Even with due screening measures in place to mitigate the risks of disease transmission related to the materials of an allograft the risks will remain and thus require a close collaboration on patient consent and vigilance [9].

Animal Products: The use of a xenograft will present ethical concerns with respect to the use of animals and therefore will require patient education, and in the case of xenografts, a reluctance to use them if there are materials that can adequately serve the purpose.

XIII. THE PERSPECTIVES OF THE FUTURE

A. Innovative Regenerative Dentistry

With the rapid growth of technology, significant improvement in the process of bone regrowth can be seen. The combination of artificial intelligence and 3D printing can lead to the emergence of tailored patient scaffolds that align with specific anatomical defects [46]. In the future, advancements in bioengineering and mathematics will lead to tailored scaffolds with desired biological factors and optimal slogon properties for specific cases [47].

B. Personalized and Biomimetic Approaches

In the future, bone regrowth will center around customized scaffolds, designed to replicate the structure of bone on various scales, with the aid of patient-specific imaging, genomic data, and computational modeling [45]. The addition of patient-derived cells and growth factors will significantly increase the body's regenerative capability and reduce the growth factor's immunogenicity.

C. Integration with Systemic Therapies

Emerging evidence supports combination approaches integrating bone grafting with systemic anabolic agents, anti-inflammatory therapies, and novel signaling pathway modulators to enhance regeneration across diverse clinical scenarios.

XIV. CONCLUSION

Bone grafting remains a cornerstone in oral and maxillofacial reconstruction, providing essential support for both functional rehabilitation and aesthetic restoration. This review highlights that although autogenous bone grafts continue to represent the gold standard due to their superior osteogenic, osteoinductive, and osteoconductive properties, alternative graft materials such as allografts, xenografts, and alloplastic substitutes offer clinically acceptable and increasingly reliable outcomes.

The effectiveness of each graft type is influenced by multiple interrelated factors, including defect size and morphology, patient-related conditions, and surgical technique. No single material can be considered universally ideal; therefore, treatment planning must adopt a case-specific, evidence-based approach to optimize clinical success.

Furthermore, the integration of adjunctive biological agents such as platelet-rich fibrin (PRF) and bone morphogenetic proteins (BMPs), along with emerging technologies like 3D printing and tissue engineering, has significantly enhanced regenerative potential and opened new possibilities for personalized treatment strategies.

Despite these advancements, challenges such as variability in clinical outcomes, lack of standardized protocols, and long-term predictability remain. Future research should focus on high-quality clinical trials, development of standardized guidelines, and further exploration of bioengineered graft materials to improve consistency and long-term success in clinical practice.

Final Recommendations

1. Patient Assessment: Systemic health, bone quality, defect description, and functional/aesthetic needs will direct material choice.

2. Multi-Modal Strategies: Autogenous bone or other primary materials and biological aids (PRF, growth factors) will increase predictability.

3. Standardization of Protocols: The application of surgical techniques from the literature (e.g., choice of barrier membrane, techniques for primary closure, and methods for post-op care) will lower the risk of complications.

4. Follow-Up Care: Ind extensive clinical and radiographic assessment for outcome measurement and late complication assessment (≥ 12 months).

5. Ongoing Research: Evidence-based practice, description of outcomes, and longitudinal studies will be the cornerstones of practice improvement.

Integrating principles of regenerative medicine, advanced biomaterials and biofabrication technologies is driving innovation in the bone grafting specialty of oral and maxillofacial surgery. The future of these disciplines will be characterized by clinical research, method and outcome standardization, and practice improvement based on evidence.

REFERENCES

1. Abushama, A. A., Alim, N., AlTuraiki, A. M., AlQahtani, T. T., Alotaibi, N. T., Alqahtani, M. M. A., & Alqahtani, N. M. (2025). Comparison of xenograft and allograft bone graft for oral and maxillofacial surgical preparation prior to dental implantation: A systematic review. *F1000Research*, 163924.
2. Andrade Santos, T. D. C., Arroyo, E., & Deliberador, T. (2025). Step-smart approach for treatment of the esthetic areas with cystic lesions using dental implants: A case report. *Journal of Clinical Medicine and Investigation*, 8702.
3. Araújo, C. R. G., Araújo, R. C. D., Araújo, C. G., Carvalho, A., Cota, L., Martins-Júnior, P., & Pelegrine, A. (2024). Bone regeneration in the anterior maxilla with titanium mesh and advanced-platelet-rich fibrin: A two-year follow-up case report. *Journal of Dental Education*, 87, D23-D154.
4. Bencharit, S., Allen, R. K., & Whitley, D. (2016). Utilization of demineralized bone matrix to restore missing buccal bone during single implant placement: Clinical report. *Journal of Dental Education*, 80, D54.
5. Bouguezzi, A., Beh, M., Habed, M. V., Chokri, A., Hentati, H., & Selmi, J. (2025). Comparative analysis of autogenous, allograft, and xenograft materials in sinus lifting procedures. *BioResearch*, 25(50).
6. Candamourty, R., & Shambulingappa, P. (2012). Biocompatibility of restorative materials. *Journal of Conservative Dentistry*, 15(2), 153-158.
7. Cardoso, M. (2014). Bone graft materials for dental implants. *Dental Implants Online Journal*, 1, 25-35.
8. Chakraborty, A., & Mandal, M. (2011). Bone graft materials and their characteristics. *Indian Journal of Oral Sciences*, 2, 10-18.
9. Chapanov, K., Stoeva, D., & Naydenov, A. (2025). Dental implant treatment with guided bone regeneration in a patient with active Crohn's disease under long-term immunosuppressive and anti-inflammatory therapy. *Cureus*, 17(5), 83439.
10. Chaudhari, S., Khade, A., Girase, V., & Dhattrak, P. (2024). A systematic review on bone grafts and biomaterials substitutes for bone regeneration. *Journal of Physics: Conference Series*, 2837(1), 012033.

11. Chavda, S., & Levin, L. (2017). Human studies of vertical and horizontal alveolar ridge augmentation comparing different types of bone graft materials: A systematic review. *Journal of Dental Education*, 81, D53.
12. Eberlikse, H., Yaylac, S., Kaprolu, D., & Ceylan, H. (2025). Multifunctional peptide nanofiber coatings enhance bone regeneration on xenograft materials. *Scientific Reports*, 15, 15743.
13. Eissa, S. A., Helal, F. A., Abaalkhail, M., Shehri, A. A., Mousa, R. A., Shabib, A. B., Angari, H. A., AlJahani, A. M., & AlDughiman, D. W. (2025). Comparative efficacy of bone graft materials in transforaminal lumbar interbody fusion: A systematic review and meta-analysis. *Journal of Spine Practice*, 4(3), 17917.
14. El Sewify, O., Abi-Rafeh, J., Legler, J., Karimi, S., Baradaran, A., & Efanov, J. (2024). Clinical, radiologic, and functional outcomes following bone grafting for metacarpal non-unions: A systematic review. *Journal of Clinical Medicine*, 13(4), 1148.
15. Elgendy, A., & Elgendy, E. (2023). Untreated mineralized dentin graft versus xenograft around immediately placed dental implants in the mandibular anterior region: A randomized controlled clinical trial. *International Journal of Oral and Maxillofacial Implants*, 38(6), 10584.
16. Ferraz, M. P. (2023). Bone grafts in dental medicine: An overview of autografts, allografts and synthetic materials. *Materials*, 16(11), 4117.
17. Gomes, L. B. R., Assuno, I. L. F., Moro, P. D., Mantovani, B. G. C., & Vasconcelos, U. S. (2025). Maxillary bone reconstruction with autogenous grafts vs. synthetic biomaterials: A comparative analysis of clinical success and implant survival rate. *Revista da Associação Paulista de Cirurgiões Dentistas*, 7(2), 1408-1421.
18. Gopalakrishnan, V., Pasumarthy, S., Chaithanya, D. J., Sunitha, K., Jalan, A., & Chouhan, C. (2025). Clinical outcomes of different bone grafting materials in maxillofacial reconstruction: An original research. *Journal of Pharmacy and Bioallied Sciences*, 17(1), 410-425.
19. Hamdan, H., Hamdan, M., & Khairallah, A. (2025). Uses of lateral bone window repositioning technique in maxillary lateral sinus elevation: A clinical and radiographic follow-up study for 121 patients for 30 to 90 months. *Journal of the Korean Association of Oral and Maxillofacial Surgeons*, 51(4), 302-318.

20. Haque, T. (2025). Assessment of bone regeneration around implants using different bone substitute materials. *Journal of Pharmacy and Bioallied Sciences*, 17(1), 79-85.
21. Hindocha, M. H., Iqbal, O., & King, E. M. (2025). Bone regeneration techniques for dental implant placement, comparing the effect of graft material on bone volume and long-term graft stability. *Journal of Dental Education*, 87(9), 238.
22. Huang, L. R., Zhong, Y. J., Zhang, X. Q., Feng, Z. R., Lai, Y. C., Wu, H. K., & Mo, A. C. (2025). Comparative evaluation of allograft particulate bone and cortical bone blocks combined with xenograft bone for labial bone defects in the aesthetic zone: A prospective cohort study. *BMC Oral Health*, 25, 443.
23. Joung, E., Park, K., Kang, N., Park, S., Kim, N. Y., Roh, Y., & Yoon, B. H. (2025). Impact of bone graft type on spinal fusion outcomes in adolescent idiopathic scoliosis: Updated meta-analysis. *Journal of Bone Metabolism*, 25(889), 889-901.
24. Khehra, A., Montesano, J. M., Tavelli, L., Chen, C. Y., & Kim, D. M. (2025). Outcomes of alveolar ridge preservation using a collagenated bovine bone xenograft: A randomized controlled trial. *Journal of Periodontology*, 70036.
25. Kim, H. G., Moon, Y. S., & Sohn, D. S. (2025). Histologic and histomorphometric evaluation of bone regeneration using human allogeneic bone graft with or without mesenchymal stem cell-conditioned media in a rabbit calvarial defect model. *Journal of Functional Biomaterials*, 16(7), 251.
26. Kim, Y. W., Cosola, S., Kim, Y. S., Park, Y. M., Covani, U., Fabbri, A., & Menchini-Fabris, G. (2025). Clinical application of rhBMP-2 and three-dimensional preformed titanium mesh with allograft and xenograft for peri-implant horizontal and vertical bone augmentation: A narrative review with technical report. *Journal of Clinical Medicine*, 14(13), 4788.
27. Kloss, F., Kammerer, P. W., & Kloss-Brandstätter, A. (2023). First clinical case report of a xenograft–allograft combination for alveolar ridge augmentation using a bovine bone substitute material with hyaluronate (Cerabone Plus) combined with allogeneic bone granules (Maxgraft). *Journal of Clinical Medicine*, 12(19), 6214.
28. Kumar, R. V., Udayshankar, V., Prakash, P., & Jain, V. (2019). Bone graft materials used in dental implants: A review. *Archives of Prosthodontics*, 14, 6.
29. Kumar, V., Naik, G. N., Tuteja, S., Bhasin, M., Chattopadhyay, D., Chowdhury, S., & Kashwani, R. (2025). Evaluation of radiographic and clinical outcomes in the use of bone

- substitutes in periapical surgery and periodontal regeneration. *Journal of Pharmacy and Bioallied Sciences*, 17(1), 1058-1025.
30. Maiti, N., Chawla, R., Rehan, A. D., Imran, A. H., Ramamurthy, J., & Hegde, S. (2026). Impact of bone growth stimulants on bone regeneration in dental implantology: A meta-analysis. *Bangladesh Journal of Medical Science*, 25(10), 86621.
 31. Mohammed, E. N., & Al-Jumaily, H. (2025). Parathyroid hormone enhances primary stability of dental implants and radiographic analysis: Randomized, split-mouth clinical trial. *American Journal of Medical Sciences*, 8(1), 1413.
 32. Moraschini, V., Louro, R. S., Son, A., Maia, M. C., Sartoretto, S., & Shibli, J. (2023). Long-term survival and success rate of dental implants placed in reconstructed areas with extraoral autogenous bone grafts: A systematic review and meta-analysis. *INPLASY*, 202390004.
 33. Nagaraj, A., Shetty, M., Thomas, B., & Hegde, R. (2024). Ridge augmentation using autograft and xenograft versus xenograft alone with simultaneous implant placement: A randomised clinical trial. *Advances in Medical and Biological Research*, 2024(0057), 57.
 34. Onic, N., Onic, C. A., Baciu, E. R., Vasluianu, R. I., Ciofu, M. L., Balan, M., & Geleu, G. L. (2023). Advanced techniques for bone restoration and immediate loading after implant failure: A case report. *Healthcare*, 11(11), 1608.
 35. Richa, R., Osman, E., Attia, N., Arakji, H., Shokry, M. (2023). Evaluation of guided bone regeneration using xenograft/APRF mixture in atrophic posterior mandible (Clinical and radiographic study). *European Science Journal*, 19(36), 9.
 36. Rodriguez, P., Alfie, N., Zmener, O., & Pameijer, C. (2024). Outcome of endodontic microsurgery using resorbable membranes and lyophilized human bone graft: A prospective randomized controlled clinical trial. *Open Access Journal of Dental Sciences*, 1047.
 37. Soares, K. H., Aguirre, J., Vilela, N., Gonçalves, P. F., Lazarin, R., Schey, K. C., & Duarte, P. M. (2025). Effect of allograft and xenograft ridge preservation on dental implant outcomes: A retrospective cohort study. *Journal of Periodontology*, 24-0852.
 38. Sokolowski, A., Theisen, K., Arefnia, B., Payer, M., Lorenzoni, M., & Sokolowski, A. (2023). A randomized clinical trial of phycogenic materials for sinus grafting with hydroxyapatite versus biphasic calcium phosphate: 2-year clinical outcomes. *Clinical Oral Implants Research*, 34(12), 14209.

39. Somngam, C., Samartkit, S., Surakit, S., Strietzel, F. P., & Khongkhunthian, P. (2025). New bone formation of biphasic calcium phosphate bone substitute material: A systematic review and network meta-analysis of randomized controlled trials (RCTs). *Bone*, 185, 636.
40. Taghizadeh, E., Negargar, S., Larki, K. N., Haghighi, R. S., & Shahoon, H. (2024). The role of guided bone regeneration in enhancing dental implant success. *Georgian Medical News*, 13(Sp1), 3681.
41. Tatli, U., Cavana, A., Tukul, H. C., & Benlidayi, M. (2025). Effects of bone augmentation on implant success and survival: A retrospective analysis with 6-year mean follow-up. *Clinical Implant Dentistry and Related Research*, 27(1), 70021.
42. Tibeic, A. I., Tibeic, S. C., Costuleanu, M., Forna, D. A., & Forna, N. (2024). Rehabilitation of alveolar bone through guided tissue regeneration with autogenous bone and xenografts: CBCT study. *Romanian Journal of Oral Rehabilitation*, 3(16), 11.
43. Timothius, C. J. C., Kilic, H. N., Gandhi, K. K., Kakar, A., & John, V. (2023). Particulate bone graft materials for periodontal and implant surgery: A narrative review and case series. *Dentistry Review*, 100068.
44. Uriostegui, C. B. D., & Gallo, P. (2025). Post-extraction vertical guided bone regeneration with a titanium-reinforced polytetrafluoroethylene membrane. *International Surgery Journal*, 20(10), 1027.
45. Win, K. Z., Pimkhaokham, A., & Kaboosaya, B. (2024). Impact of interproximal features on marginal bone level changes of autograft, allograft, and xenograft after functional loading: A retrospective study. *Journal of Indian Orthodontic Society*, 67(24).
46. Zampara, E., Alshammari, M., De Bortoli, J., Mullings, O., Gkisakis, I. G., Benalczar Jalkh, E. B., Tovar, N., Coelho, P., & Witek, L. (2022). A histological and histomorphometric evaluation of an allograft, xenograft, and alloplast graft for alveolar ridge preservation: Randomized clinical trial. *Journal of Dental Education*, 85, D21-D12.
47. Zhong, R., Yu, G., Wang, Y., Fang, C., Lu, S., Liu, Z., Gao, J., Yan, C., Zhao, Q. (2023). Research on the influence of the allogeneic bone graft in postoperative recovery after MOWHTO: A retrospective study. *Therapeutics and Clinical Risk Management*, 400354.