International Journal of Research in Medical Sciences
Raghavan R et al. Int J Res Med Sci. 2025 Sep;13(9):3915-3920
www.msjonline.org
pISSN 2320-6071 | eISSN 2320-6012

DOI: https://dx.doi.org/10.18203/2320-6012.ijrms20252820

Review Article

Osseointegration in dental implants

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Received: 20 July 2025
Accepted: 19 August 2025

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ABSTRACT

Osseointegration refers to the direct structural and functional connection between living, organized bone and the surface of a load-bearing implant. It plays a vital role in implant stability and is regarded as essential for both implants loading and the long-term clinical success of endosseous dental implants. The implant–tissue interface represents a highly dynamic zone of interaction, involving not only issues related to biomaterials and biocompatibility but also changes in the mechanical environment. The process of osseointegration begins with an initial mechanical interlock between the implant and the surrounding alveolar bone, followed by biological fixation through ongoing bone growth and remodeling at the implant surface. Given its complexity, numerous factors affect both the formation and maintenance of bone at the implant interface. This review aims to evaluate the current understanding of clinical assessment methods and the key factors influencing the success and failure of osseointegrated dental implants.

Keywords: Ossseointegration, Bone, Implant

INTRODUCTION

Osseointegration is a fundamental concept in implant dentistry, describing the biologically driven process by which dental implants achieve stable and long-lasting anchorage in bone.[1,2] It is defined as a time-dependent healing phenomenon where a rigid, symptom-free connection forms between bone and the surface of an artificial material under functional load.[3] Unlike earlier theories suggesting a fibrous tissue interface, osseointegration relies on direct contact between bone and implant without intervening soft tissue, ensuring durability and effective load transfer.[4]

THEORIES OF INTEGRATION

Two primary theories have been proposed to explain implant integration with bone:

Fibro-osseous integration

First suggested by Weiss in 1986, this concept involved implant stabilization through dense, healthy collagenous tissue interposed between the implant and bone. The proposed “peri-implant membrane,” sometimes referred to as a pseudo-ligament, was thought to mimic the periodontal ligament of natural teeth and even provide osteogenic potential. However, this theory lacked evidence, as collagen fibers aligned parallel to the implant surface did not effectively transmit functional forces. Loading led to widening of the fibrous capsule, inflammation, progressive bone resorption, and ultimately implant failure.[5]

Osseointegration

Popularized by Brånemark in 1982, osseointegration describes direct bone-to-implant contact without any intervening non-osseous tissue. This intimate connection permits predictable force distribution and long-term stability of the implant under functional loads.[1,6]

STAGES OF OSSEOINTEGRATION

Misch's concept divides osseointegration into two main phases, each with two sub-stages.[7]

Surface modeling

Sub-stage 1: Woven callus formation (0-6 weeks): An immature bone matrix forms rapidly around the implant. This woven bone is characterized by random collagen orientation, irregular osteocytes, and low mineral density.

Sub-stage 2: Lamellar compaction and maturation (6-18 weeks): The initial woven bone remodels into stronger lamellar bone with organized structure, enhancing mechanical strength to withstand functional loading.

Remodeling and maturation

Sub-stage 3: Interface remodeling (6-18 weeks): The provisional callus is gradually resorbed and replaced by viable bone at the implant interface, establishing a stable bond with the surrounding native bone.

Sub-stage 4: Compact bone maturation (18-54 weeks): Through continuous modeling and remodeling, compact bone matures further, reducing callus volume and improving the structural integration of the implant.

PHASES OF OSSEOINTEGRATION

The process can also be conceptualized in three overlapping biological phases:

Osteophilic phase

Recruitment and attraction of osteogenic cells to the implant surface.

Osteoconductive phase

Formation of new bone guided along the implant surface.

Osteoadaptive phase

Long-term remodeling of bone in response to functional loading.[8]

Key factors for successful osseointegration-(Alberktsson)

Key factors are as follows-implant biocompatibility, implant design, implant surface characteristics, bone factors, host factors/patient factors, surgical considerations, loading conditions, prosthetic considerations.[2,9,10]

IMPLANT BIOCOMPATIBILITY

Biocompatibility is central to osseointegration success, referring to the ability of implant materials to integrate with bone without provoking adverse reactions. Materials can be classified by their biological response: biotolerant materials tend to develop a fibrous capsule and rely on distant osteogenesis; bioinert materials promote close bone apposition, enabling contact osteogenesis; and bioactive materials encourage direct bonding by stimulating new bone formation at the interface.

Titanium and its alloys remain the most widely used implant materials due to their exceptional corrosion resistance and biocompatibility.[11,12] A protective oxide layer forms within seconds, ensuring chemical stability. Alloys such as Ti-6Al-4V (Extra low interstitial) balance strength and elasticity, although their modulus remains 5-10 times higher than cortical bone. Newer titanium alloys incorporating elements like niobium, zirconium, and molybdenum have further improved corrosion resistance. Commercially pure titanium is available in several grades based on oxygen content, with higher grades offering increased strength.

Ceramics, both bioinert (such as alumina and zirconia) and bioactive (like hydroxyapatite and bioglass), provide excellent biocompatibility and esthetics, with minimal thermal conductivity. However, they exhibit low tensile and shear strength under fatigue loading, limiting their use in high-stress applications. Polymers, despite advances such as PEEK, remain limited by low mechanical strength, susceptibility to environmental changes, and challenges in sterilization, making them less suitable as primary implant materials. Ceramics and polymers have their limitations but are under continuous development.[13]

IMPLANT DESIGN

Implant design plays a critical role in achieving primary stability and long-term integration. Key considerations include length, diameter, shape, and thread pattern.[14] A wider diameter increases functional surface area and improves fracture resistance while matching the ridge width for optimal emergence profile.

The macrogeometry of the implant affects surgical placement and load distribution. Smooth-sided cylindrical designs rely on surface coatings or microstructural modifications to ensure effective force transfer. Tapered implants distribute load efficiently but must balance taper angle, as excessive taper reduces surface area and may compromise stability. Threaded implants offer superior initial stability by increasing functional surface area and limiting micromovement during healing. Thread shapes such as V-shaped, buttress, reverse buttress, square, and spiral designs further influence load distribution and surgical handling.

IMPLANT SURFACE CHARACTERISTICS

Surface modification aims to enhance osseointegration by increasing surface area, improving roughness, and promoting better bone bonding. Methods can be categorized as additive (e.g., sintering, titanium plasma spraying, hydroxyapatite coating, anodization) or subtractive (e.g., grit blasting, acid etching, laser peening, mechanical polishing). Advanced nano-modification techniques such as ion implantation, ion beam deposition, and nanocrystal coatings-including calcium phosphate or hydroxyapatite-have further improved the biological response by facilitating cellular adhesion and accelerating bone formation.[15,16]

BONE FACTORS

Bone quality and quantity are essential determinants of implant success. Quality encompasses skeletal size, trabecular architecture, matrix properties, mineralization, and three-dimensional orientation of trabeculae, all of which influence the bone's capacity to support functional loads. Sufficient bone volume ensures proper implant placement, stability, and long-term performance.[17]

HOST/PATIENT FACTORS

Patient-related considerations include age, medical history, oral hygiene, parafunctional habits, and the condition of the host bone bed. Implants are generally avoided in patients under 18, as ongoing skeletal growth can compromise long-term outcomes. In such cases, removable partial dentures or non-invasive composite bridges may be preferred until growth is complete.

Medical history must be thoroughly reviewed to identify contraindications. Relative contraindications include active malignancies, bleeding and blood cell disorders, cardiac complications, and certain infections. Absolute contraindications involve uncontrolled systemic diseases, osteoradionecrosis, or immunosuppression in specific contexts.

Certain medications also impact osseointegration. Drugs like simvastatin and bisphosphonates can enhance bone formation and stability. Conversely, anticoagulants such as warfarin and heparin, along with medications like cyclosporine, methotrexate, cisplatin, and some NSAIDs, may inhibit osseointegration by affecting bone metabolism and healing.

Oral hygiene is another vital factor, as poor hygiene increases the risk of peri-implantitis and failure. Patients with parafunctional habits, such as bruxism and clenching, place excessive stress on implants and require careful management, sometimes with adjunctive therapy to control these forces.

Smoking is a well-known risk factor, impairing healing, angiogenesis, and bone integration. Preoperative smoking cessation is strongly recommended.[18,19]

The host bone bed should ideally have sufficient height, width, density, and overall health. Prior irradiation, severe ridge resorption, or systemic bone diseases like osteoporosis can create challenging conditions requiring tailored treatment planning.

SURGICAL CONSIDERATIONS

Successful osseointegration depends on precise surgical technique and atraumatic tissue handling. Minimizing trauma preserves blood supply and promotes healthy healing.[20] Profuse irrigation prevents thermal damage, as bone temperatures exceeding 47 °C for even one minute risk necrosis. Recommended drilling speeds are typically below 2000 rpm with sharp instruments.

Anatomical landmarks guide safe placement. For example, implants should be at least 1 mm below the floor of the maxillary sinus, 5 mm anterior to the mental foramen, and maintain adequate clearance from adjacent roots and implants. Incision designs, such as papilla-sparing mid-crestal or releasing incisions, balance visibility and tissue preservation during placement.

LOADING CONDITIONS

Loading protocols influence bone adaptation and stability.[21] Delayed loading, popularized by Brånemark, involves a submerged healing period of approximately three months in the mandible and six months in the maxilla to allow undisturbed integration. This approach includes countersinking implants below crestal bone, achieving soft tissue coverage, and avoiding functional loading during healing. Though predictable, it requires longer treatment times and multiple surgeries.

Immediate loading delivers functional forces within days of placement, suitable for dense bone (e. g., D1 quality), long implants, or designs with optimized threading to enhance initial retention. Progressive loading involves gradually increasing functional load, allowing bone to adapt biomechanically while minimizing the risk of micromotion during early healing.

PROSTHETIC CONSIDERATIONS

Prosthetic design must ensure even load distribution and minimize stress concentrations. Factors include the number, size, arrangement, and angulation of implants, as well as the quality and volume of the bone-implant interface.[22] Implants aligned with functional loads in dense bone demonstrate superior outcomes compared to short, narrow implants placed off-axis in less dense bone.

Excessive angulation (more than 20° off-axis) magnifies occlusal forces, risking bone loss and mechanical failure. Connecting implants to natural teeth in fixed partial dentures creates cantilever forces that can double the applied load, leading to abutment or screw fracture, cement failure, and bone loss.

Passive fit of frameworks is essential to avoid stress concentrations, while over-tightening screws can damage the bone-implant interfaces and the compromise integration.

METHODS TO DETERMINE OSSEO-INTEGRATION

Assessing the stability and integration of dental implants with surrounding bone is essential for ensuring long-term success. Several diagnostic methods, both invasive and non-invasive, have been developed to evaluate the extent of osseointegration. Each technique offers unique advantages and limitations, and clinicians often use them in combination to gain a comprehensive understanding of implant stability. Multiple diagnostic methods provide assessment: radiographs, insertion torque, reverse torque test, percussion test, pulsed oscillation waveform, and resonance frequency analysis (RFA).[23-25]

Radiographic assessment

Radiography is one of the earliest and most widely used non-invasive techniques to evaluate the condition of dental implants. It allows for assessment at any stage of treatment, providing valuable information about marginal bone levels and potential peri-implant pathology. However, radiographs have inherent limitations. If the central ray does not align precisely with the implant's center, image distortion can occur, potentially leading to misinterpretation. Furthermore, as a two-dimensional modality, radiographs fail to capture facial and lingual bone contours and cannot directly measure bone density or quality. Importantly, radiographic changes typically become evident only after bone demineralization exceeds approximately 40%, limiting their sensitivity for early detection.

Insertion torque analysis

This method assesses the force required to place an implant into the prepared osteotomy site, usually measured manually with a torque wrench. It is widely used during implant placement as an indicator of primary stability. While higher insertion torque values generally suggest better initial stability, the technique cannot reliably assess bone quality or predict long-term integration.

Reverse torque test

Introduced by Roberts et al reverse torque test measures the removal torque value (RTV) by applying a counter-clockwise force to the implant via a torque wrench. Although it provides direct measurement of mechanical stability at the bone-implant interface, this method is inherently destructive. Applying reverse torque can cause irreversible plastic deformation of the peri-implant bone, increasing the risk of implant failure, especially in sites with poor bone quality.

Percussion test

The percussion test is among the simplest clinical methods for evaluating implant stability. It relies on the sound generated when the implant is lightly tapped with a metallic instrument. A clear, high-pitched sound is generally associated with good stability, whereas a duller sound may indicate mobility or poor integration. Despite its ease of use, the test is highly subjective, dependent on the clinician's experience, and cannot serve as a standardized or quantitative assessment.

Pulsed oscillation waveform analysis

This technique evaluates the mechanical and vibrational characteristics of the bone-implant interface by applying a small pulsed force and analyzing the resulting vibration frequency and amplitude. While it offers detailed information about the interface's mechanical behavior, the method is highly sensitive to variations in probe position and angulation, which can affect reliability and reproducibility.

Resonance frequency analysis

Resonance frequency analysis is a non-invasive, objective, and widely accepted method for assessing implant stability. It involves attaching a two-piece transducer to the implant or abutment. One component vibrates in response to an applied signal, while the other acts as a receiver, measuring the response and converting it into a numerical value displayed as the implant stability quotient (ISQ). ISQ values range from 0 to 100, with values above 65 typically indicating well-integrated implants and values below 50 suggesting poor osseointegration. RFA provides clinicians with a reliable, repeatable tool for monitoring implant stability over time, guiding decisions about loading protocols and patient management.

RECENT ADVANCES IN OSSEOINTEGRATION RESEARCH

Over the past decade, considerable progress has been made in understanding and enhancing the osseointegration process through material science, surface engineering, and biological modulation. Nanotechnology, bioactive coatings, stem cell therapy, and digital dentistry have advanced implant success rates.[15,26,27]

Nanotechnology and surface engineering

Modern implant surfaces utilize nanostructured coatings and modifications that mimic the natural bone environment at the molecular scale. Nanotopographies on titanium surfaces increase protein adsorption, improve osteoblast attachment, and stimulate earlier bone formation. Techniques such as anodization, electron beam deposition, and plasma spraying allow controlled nano-roughness, which has been shown to accelerate the healing timeline and improve bone-implant contact percentage.

Bioactive coatings and biomolecules

Incorporating bioactive molecules like bone morphogenetic proteins (BMPs), growth factors, and peptides onto implant surfaces further stimulates osteogenesis. Hydroxyapatite and calcium phosphate coatings, when combined with these biological agents, promote a stronger and faster integration. Research into coating implants with anti-inflammatory agents aims to reduce peri-implantitis risk.

Stem cells and regenerative approaches

Mesenchymal stem cells (MSCs) derived from bone marrow or adipose tissue are being investigated as adjuncts to enhance bone regeneration around implants. These cells can be seeded on scaffolds or introduced locally during implant surgery to encourage faster and more robust osseointegration, especially in compromised bone conditions.

Digital dentistry and precision implantology

The use of computer-aided design and manufacturing (CAD/CAM), combined with cone-beam computed tomography (CBCT) and 3D printing, allows for highly precise implant placement tailored to patient-specific anatomy. Guided surgery reduces surgical trauma and optimizes implant positioning to improve biomechanical loading and osseointegration outcomes.

CLINICAL IMPLICATIONS AND CONSIDERATIONS

Management of compromised bone sites

Patients presenting with insufficient bone volume or quality due to atrophy, trauma, or systemic disease require special management to achieve successful osseointegration. Bone grafting, sinus lifts, and use of bone substitutes are common adjunctive procedures. Novel biomaterials such as synthetic grafts with osteoinductive properties are continuously developed to improve graft integration and implant success rates.[18]

Peri-implantitis and maintenance

Long-term implant success depends not only on initial osseointegration but also on maintaining peri-implant tissue health. Peri-implantitis, an inflammatory condition leading to bone loss around implants, poses a significant threat. Effective oral hygiene, routine professional maintenance, and early intervention strategies are critical for prevention and management.[28] Surface modifications that resist bacterial colonization are an area of ongoing research.

Load management and prosthetic design

The relationship between occlusal forces and implant longevity is well established. Excessive or misdirected loading can cause microfractures in bone and disrupt osseointegration. Prosthetic designs should aim to distribute occlusal loads evenly, avoid cantilever effects, and maintain passive fit to minimize mechanical complications.

CHALLENGES AND LIMITATIONS

Despite advances, several challenges persist in clinical practice.[19,29]

Variability in patient response

Individual differences in bone biology, systemic health, and lifestyle habits affect healing and integration unpredictably.

Aging population

Older patients often exhibit reduced bone regenerative capacity and co-morbidities, complicating osseointegration.

Systemic diseases

Conditions such as diabetes, osteoporosis, and autoimmune disorders impair bone healing and increase implant failure risk.

Medication effects

Long-term use of bisphosphonates, corticosteroids, or immunosuppressants may negatively influence osseointegration.

Infection control

Strict aseptic surgical technique and post-operative care are imperative to prevent early failures.

FUTURE PERSPECTIVES

The future of osseointegration research and clinical practice points toward personalized and biologically driven therapies.

Smart implants

Development of implants capable of sensing mechanical load and delivering localized drugs or growth factors is underway.

Regenerative medicine integration

Combining implants with tissue-engineered constructs and gene therapy may revolutionize bone regeneration.

Artificial intelligence

AI-assisted diagnostics and treatment planning promise to optimize implant placement, predict outcomes, and customize patient care.

Minimally invasive techniques

Refinements in surgical approaches aim to reduce healing time and enhance patient comfort without compromising osseointegration.[27,30]

CONCLUSION

Thorough understanding and application of forces affecting osseointegration, the mechanism, factors and biological process of osseointegration in clinical practice is the key factor of success. As osseointegration is a multifactorial entity, achieving osseointegration of the endosteal dental implants needs understanding of the many clinical parameters.

Funding: No funding sources
Conflict of interest: None declared
Ethical approval: Not required

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Cite this article as: Raghavan R, Shajahan PA, Prasad NG. Osseointegration in dental implants. Int J Res Med Sci 2025;13:3915-20.