ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr1088

Rooted in Bone: The Role of Osseointegration in Dental Implantology

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Publication Date: 2025/05/02

Abstract: In a society that places a high value on aesthetics, the use of implants for the prosthetic rehabilitation of lost teeth has become increasingly popular among both patients and clinicians. Osseointegration is the biotechnical process behind implants, which has been studied for years due to advancements in understanding its cellular and molecular mechanisms. Researchers are now focusing on factors influencing osseointegration, focusing on even the smallest details. The stability of implants, particularly secondary stability, is influenced by bone formation and integration with surrounding osseous tissues. Factors affecting osseointegration include implant characteristics, bone quantity and quality, and local and systemic host conditions. The timing and protocols for functional loading also play a crucial role. Continuous monitoring of osseointegration status is essential to mitigate challenges and ensure successful implants. This review aims to cover the mechanisms and influencing factors of osseointegration, along with methods for its assessment, and will conclude with a discussion on recent advancements and future directions in dental implantology to improve the osseointegration process. The goal of this review is to inspire further technological developments that enhance osseointegration.

Keywords: *Dental Implant, Osseointegration, Implants, Implant Stability.*

How to Cite: Dr. Nayan P. Joshi; Dr. Khalid M. Agwani; Dr. Ramank Mathur; Dr. Pooja Ghosh; Dr. Kunal Tejnani; Dr. Shrishti Mishra (2025). Rooted in Bone: The Role of Osseointegration in Dental Implantology. *International Journal of Innovative Science and Research Technology*, 10(4), 2164-2169. https://doi.org/10.38124/ijisrt/25apr1088

I. INTRODUCTION

Millions of people around the world suffer from tooth loss, a common event that affects oral function, aesthetics, and general quality of life. Several issues accounting mastication, issues related to speech, aesthetics, movement of adjacent tooth and bone loss are all related to or are result of lost dentition. Dental implants have become a reliable adjunct as replacement or alternative for mutilated, non-restorable or missing tooth serving several advantages. Dental implantology as a treatment procedure has crossed numerous milestones as a result of in-depth research, advancements, and successful understanding of osseointegration. The surface of a load-bearing dental implant and living bone tissue can directly connect structurally and functionally as a result of this phenomenon.

Per-Ingvar Branemark developed the idea of osseointegration, the concept of osseointegration expanded restorative options for partially or fully edentulous patients, benefiting both patients and clinicians through biotechnology. Osseointegration is broadly identified as a crucial element of implant stability and is necessary for the long-term sustainability of dental implants.

Multiple definitions for osseointegration were proposed in different time frames by different authors, researchers, and clinicians, some of which are as follows-

- Branemark defined osseointegration as a direct structural and functional connection between ordered living bone and the sur face of a load-carrying endosseous implant at the light microscopic level.[1]
- The American Academy of Implant Dentistry (1986) defined it as contact established without the interposition of nonbone tissue between normal remodelled bone and an implant, entailing a sustained trans fer and distribution of load from the implant to and within the bone tissue.
- The glossary of prosthodontic terms-8 (GPT-8) defined it as the apparent direct attachment or connection of osseous

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr1088

tissue to an inert, alloplastic material without intervening connective tissue.[3]

- The glossary of prosthodontic terms-10 (GPT-10)[4] defined it as-

- ✓ The apparent direct attachment or connection of osseous tissue to an inert, alloplastic material without intervening fibrous connective tissue.
- ✓ The process and resultant apparent direct connection of an exogenous material's surface and the host bone tissues, without intervening fibrous connective tissue present.
- ✓ The interface between alloplastic materials and bone; orig, Per-Ingvar Branemark, physician/professor/surgeon, Sweden, 1982

Since 1952, Lund and Goteborg universities have been researching osseointegration, a concept attributed to microscopic studies on rabbit fibula bone marrow. In the 1960s, studies showed the possibility of osseointegration, with bone tissue growing into titanium chambers. However, histological evidence remained inadequate until the 1970s. Schroeder demonstrated direct bone-to-implant contact in the mid-1970s,[5] and Cameron et al.[6] suggested that bone grows on biocompatible materials when movement is restricted.

Osseointegration is a complex process involving biological, mechanical, and material factors. Key principles include surface topography, biocompatibility, mechanical stability, and biological compatibility. Osseointegration is a pre-requisite for implant placement in various clinical treatment procedures ranging from single-tooth replacement, multiple-tooth replacement, and edentulous patients. Understanding these principles, leads dental professionals optimize implant placement procedures, ensuring predictable and successful outcomes for patients. However an important aspect for osseointegration, that is the quality of bone has been overlooked and lacks evidence in the literature hence relevance and research related to this aspect of the subject is to be dwelled and explored. Given the aforementioned, it is evident that modern dental implants and osseointegration must continue to advance. The purpose of this review is to incorporate available information about dental implant osseointegration that is found in current literature to bridge the gap related to the subject.

II. AUGMENTING THE GRASP OF OSSEOINTEGRATION

➢ *The Cellular and Molecular Aspects of Osseointegration.*

A physiological occurrence associated with the integration of bone and implant is defined by the process of primary bone healing. The procedure begins with the placement of the implant into the bone, resulting in the swift formation of a water layer in the surrounding environment within nanoseconds, thereby promoting the absorption of proteins and other crucial molecules.[7] Subsequently, within a timeframe ranging from 30 seconds to several hours, proteins from the intercellular matrix, initially sourced from interstitial fluid and blood and subsequently influenced by cellular activity, enveloping the surface of the implant. This coating exhibits a structure, composition, and orientation determined by the type of surface present.[8] The protein layer initiates cell adhesion, migration, and differentiation, interacting with the implant surface for hours or days. Additional adjustments are introduced by extracellular matrix proteins, cytoskeletal proteins, cell surface-binding proteins, and chemical characteristics. Collagen I, fibronectin, osteopontin, osteodentin, osteoadrin, bone sialoprotein, and certain plasma proteins like α2HS glycoprotein facilitate data transmission by acting as messengers and cell adhesion interfaces.[9]

A titanium oxide layer is created by air exposure, which enhances wear resistance and shields the surface from biological damage. Because it permits the adsorption of Ca2+ and PO4-3-, this layer also affects bio-mineralization. A thin layer of titanium oxide develops when titanium is exposed to air, strengthening its resistance to wear and shielding its surface from biological damage. This layer facilitates the adsorption of Ca2+ and PO4-3-, which also affects biomineralization. Implant incorporation, bone mass adaptation, and bone structure adaptation to the load are the three phases of osseointegration.[10]

➢ *Osseointegration versus Fracture Healing*

Osseointegration, unlike fracture healing, involves fully differentiated progenitor cells into osteoblasts, leading to intramembranous ossification, unlike fracture healing where initial woven bone is replaced by lamellar bone.[11] A significant distinction can be found in the presence or absence of an implant and its surface characteristics. In contrast to fracture sites, a substantial portion of the bone gap is occupied by the implant itself, thereby reducing the area that requires regeneration by new bone. Additionally, the properties of implant's surface, along with innovative surface treatments, promote a favourable response from osteogenic cells.[12]

III. FUNDAMENTAL ELEMENTS FOR ACHIEVING OSSEOINTEGRATION SUCCESS

The effectiveness of osseointegration relies on the complex interaction of multiple factors, including the biocompatibility of the implant material, the macro- and microscopic characteristics of the implant surface, the design features of the implant, the morphology and quality of the bone at the site of implantation, the surgical techniques utilized, the stability of local and systemic health during the healing period, and the loading conditions and protocols adhered to.[13]

A. Factors Determining the Success and Failure of Osseointegration.

The successful longevity of an endosseous implant relies on the careful oversight of the osseointegration process, which must be regulated by addressing the multiple factors that can impact it.

➢ *Implant Characteristics.*

- *Geometry of Implant*

The development of bone tissue primarily takes place on the raised or protruding features of an implant's surface, such as the ridges, crests, and thread edges. The design of the

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr1088

implant is also a critical factor, as it determines the surface area for stress distribution and the primary stability of the implant. Threaded implants offer a more extensive functional surface area than smooth or tapered implants, allowing for secure fixation and reducing the microenvironment during the healing phase. Conversely, smooth-sided implants necessitate additional surface treatments, and the presence of a taper decreases the available surface area for osseointegration. Studies have demonstrated that implants with grooves oriented at +60° downwards to the long axis attract a greater density of osteocytes in the peri-implant region.[14]

- *Width and Length of Implant*

The greater the dimensions of an implant, the greater will be the surface area provided for osseointegration. However, increasing the length beyond a limit must be avoided as it may not allow the proportionate transfer of forces.[14]

- *Micro-Design of Implant*

Implant surface modification, usually with pure titanium, produces a biocompatible and bioactive surface that promotes osteoblast adhesion, proliferation, and differentiation without integrating. To encourage osteogenesis, boost platelet gene adhesion, and encourage bone growth, methods such as dual acid-etching, titanium plasma-sprayed surfaces, and sandblasted, large-grit, acid-etch (SLA) implant surfaces have been employed.[15]

By increasing the functional surface area and bone-to-implant interface, hyphapatite coatings promote osteogenic cell morphogenic activities and speed up the formation of interfacial bone. Early osteogenesis is stimulated by a capacitively coupled electric field, which speeds up recovery and makes early functional loading possible. Positive outcomes have been observed when bovine osteogenic protein is inserted into unaltered sockets using implants.[16]

B. Bone Characteristics

The bone acts as the substrate for implant placement, and its health is vital for successful osseointegration. Bones that have undergone radiation treatment or are compromised by osteoporosis create significant obstacles to this process. It is therefore advisable to wait for a healing period post-radiation before proceeding with implant placement, or to utilize hyperbaric oxygen therapy to improve healing conditions. Other factors that can negatively impact osseointegration include a history of smoking and systemic conditions such as diabetes mellitus or hypertension. Additionally, ridge augmentation or bone grafting may be required to address the loss or insufficient volume of alveolar ridges, facilitating effective osseointegration.

C. Intraoperative Factors

To prevent unintentional bone necrosis, it is important to restrict tissue damage and maintain bone temperatures below harmful levels by utilizing low-speed surgical drilling. For instance, a temperature of 47°C for one minute can initiate necrosis in bone tissue.

D. Implant Loading

Osseointegration relies on implant stability, and various loading protocols have been used, resulting in varying clinical results. Studies have shown that immediate occlusal loading can achieve similar survival rates to early loading, but not when compared to conventional methods. However, peri-implant bone formed around functionally loaded implants is thicker, indicating no significant difference in bone-to-implant contact percentage.[17,18]

IV. ASSESSMENT OF OSSEOINTEGRATION

Regular monitoring of osseointegration is critical for implant success, with secondary implant stability providing insight into quality. Due to concerns regarding invasiveness, a variety of methods are now in use, such as radiographic assessments, cutting torque resistance, reverse torque measurements, and model analyses.

The histological examination provides extensive details about bone quality, including contact percentage, the types of bone formed, and the morphological attributes of osteocytes. Key factors assessed include size, orientation, alignment, quantity, density, proximity to blood vessels, and the interconnectivity of lacuno-canalicular systems. However, owing to its invasive nature, this technique is usually confined to nonclinical investigations or experimental studies.[19]

Radiographic visualization is recognized as a non-invasive method for assessing osseointegration, as demonstrated in the study by Chopra et al., which utilized digital orthopantomograms alongside cone-beam computed tomography (CBCT). The results indicated that osseointegration at the apical section of the implants was measured at 0.03 mm, with a crestal bone height of 0.04 mm and an apical measurement of 0.01 mm after a three-month duration. Both techniques are effective for evaluating osseointegration, but it is advisable to use computed tomography when it provides the most significant benefits with the least amount of radiation exposure.[20] Jung et al.'s study utilized monochromatic synchrotron radiation to examine the bone-implant interface, comparing the resulting image quality with micro-computed tomography and traditional dental radiographs. The results showed that the synchrotron radiation imaging method revealed more intricate details of bone contact, potentially impacting future studies on osseointegration assessment.[21]

Within clinical practice, various tests, such as the tensional test and osseointegration test, may be either invasive or non-invasive. In earlier methodologies, tensional tests involved the removal of the implant plate from the bone.[22] Developed by Roberts et al. and Johansson and Alberterktsson, the reverse torque test is used to assess secondary stability. Nonetheless, it may cause implant rotation and damage the bone-implant interface. Furthermore, because of variations in patient thresholds and the materials used for implants, it cannot accurately quantify osseointegration.[13,23]

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Non-invasive methods, such as surgeon perceptions of cutting resistance and seating torque during implant placement, measure primary implant stability but do not consider osseointegration during healing stages. Kaneko et al. developed a method that employs forced excitation of steady-state waves to investigate mechanical vibrations occurring at the bone-implant interface. Meredith's resonance frequency analysis assesses bone density over various time intervals through the use of vibrations and structural evaluation. An amplifier generates a sinusoidal signal that causes the implant to fracture.[24] The method of high-frequency resonance analysis, which incorporates Osstell and Osstell Mentor, is frequently utilized for the assessment of osseointegration in clinical practice.[25]

V. MODERN DEVELOPMENTS AND PROSPECTIVE INNOVATIONS IN IMPLANT TECHNOLOGY TO FOSTER OSSEOINTEGRATION

Implant surface topography significantly influences cell adhesion and the differentiation of osteoblasts, making it imperative to achieve high primary stability and promote granulation tissue formation. Instrumentation should be conducted between the inner and outer threads to enhance bone remodelling and facilitate the migration of osteogenic cells.[26]

The relationship between microtopography and microroughness plays a crucial role in supporting the attachment of osteogenic cells and enhancing bone deposition in the 1-100 μm range. Several manufacturing techniques can be employed to optimize this effect.

While microtopography functions primarily at the cellular level in osseointegration, nano-topography is thought to engage with proteins as well. It affects osseointegration through a combination of physical, chemical, and biological pathways, thereby improving the adhesion of osteogenic cells and supporting the osseointegration process.

UV radiation treatment of implant surfaces results in increased bioactivity and osseointegration potential, stemming from modifications to the titanium dioxide layer. Moreover, UV light fosters osteoconductivity by enhancing the interactions of cells and proteins with the implant surface. This treatment also minimizes surface hydrocarbons, improves wettability, elevates protein adsorption, and encourages cellular attachment to titanium surfaces, effectively restoring bioactivity that may diminish over time due to degradation.[27]

Coating implant surfaces with growth factors like platelet-derived growth factors, transforming growth factor-beta, fibroblast growth factor, vascular endothelial growth factor, and bone morphogenetic proteins, in addition to extracellular matrix proteins, peptides, and signalling molecules such as sclerostin, promotes a faster osseointegration process, functioning as inherent facilitators. Furthermore, these surfaces are also enhanced with pharmaceuticals like bisphosphonates to counteract any limiting local or systemic host factors.[28]

VI. RECENT ADVANCES IN DENTAL IMPLANT BIOMATERIALS

Metals and alloys are widely used as implant materials due to their biocompatibility, acceptable physical and chemical properties, particularly in dental implants.[29] The use of zirconia and alumina-toughened zirconia as biomaterials for dental implants is prevalent, owing to their remarkable flexural strength, durability against fractures, effective osseointegration, and pleasing aesthetic characteristics.[30]

Another metal being researched for its application as a biomaterial in dental implants is tantalum. The porous variant of tantalum demonstrates superior corrosion resistance and has proven successful as an implant material in orthopaedic surgeries, aiding in angiogenesis and enhancing wound healing.[31] PEEK, an organic polymer, is increasingly used as a biomaterial for dental implants and prosthetics due to its higher elasticity modulus, uniform distribution of masticatory forces, excellent colour stability, and greater abrasion resistance compared to zirconia.[32] PEEK, when surface modified, enhances osseointegration by enhancing cell adhesion, proliferation, and osseointegration, according to a systematic review by Mishra and Chowdhary on PEEK as an alternative to titanium dental implants.[33] It is imperative to conduct more clinical trials to establish PEEK as a potential replacement for titanium in the realm of dental implant biomaterials.

VII. SURGICAL TECHNIQUES TO ENHANCE DENTAL IMPLANT OSSEOINTEGRATION

The success of osseointegration relies on the primary stability of the dental implant during insertion. Undersized drilling, a technique using a smaller drill diameter than the implant fixture, has gained popularity to ensure adequate insertion torque, especially in areas with lower alveolar bone density. This method enhances implant primary stability, as demonstrated in an experimental study by Tobassum et al. and a systematic review by Stocchero et al.[34,35]

The osteotome technique is a surgical method that improves osseointegration by increasing the primary stability of dental implants. This is achieved through the sequential expansion and condensation of alveolar bone with progressively larger osteotomes, which minimizes micro deformations.[36] It is recommended that the osteotome technique be utilized as an effective means to enhance primary implant stability, especially when working with low-density alveolar bone, in contrast to the conventional drilling technique.[37]

Osseodensification refers to a drilling approach that effectively preserves and compacts bone during the preparation of the implant site, leading to improved osseointegration and enhanced initial stability. This technique works by compressing bone chips against the osteotomy walls, forming a strong layer of autogenous bone around the

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implant once it is inserted, unlike the methods used in traditional drilling.[38] A systematic review and meta-analysis by Inchingolo et al. compared the effectiveness of osseodensification with traditional drilling methods. The results demonstrated that osseodensification consistently yielded superior outcomes in all evaluated metrics, underscoring its advantages for promoting osseointegration, especially in regions characterized by lower bone density.[39]

However, the results on osseodensification are primarily from animal studies; hence, clinical trial in human are warranted to confirm those results.

VIII. CONCLUSION

Osseointegration is vital for the success of dental implants, integrating living bone with implant surfaces for long-term stability. Advanced surface modifications, biomaterials, and surgical techniques have evolved this process, which is influenced by factors such as implant design, bone quality, and patient health. Implant stability and compatibility are improved by innovations like growth-factor coatings, UV-treated implants, and novel biomaterials like PEEK and zirconia. Monitoring is enhanced by non-invasive evaluation techniques such as resonance frequency analysis and radiographic imaging. Osteodensification and osteotome are two methods that improve primary stability, especially in low-density bone. Research is still being done to solve problems and improve implant performance.

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