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Osseointegration Dynamics: Insights into the Dental Bone-Implant Interface

Sirus Safaee[1*], Mahdis Nesabi[2], Mahyar Nesabi[3], Faezeh Mamizad Moghtader[3]

1.Department of Prosthetic Dentistry, Graduate School of Biomedical Sciences, Nagasaki University, Japan-
2.Department of Dental and Biomedical Materials Science, Graduate School of Biomedical Sciences, Nagasaki University, Japan
3.Department of Dental and Periodontal Research Center, Tabriz University of Medical Sciences, Tabriz; Iran.
* Corresponding Author: Sirus Safaee, sirus.safaee@nagasaki-u.ac.jp

Sirus Safaee
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Abstract

The interface between a bone and an implant, referred to as the bone-implant interface (BII), plays a critical role in determining the success and long-term stability of dental implants. This comprehensive review delves into the various factors that influence the BII. The design of the implant and the treatments applied to its surface are fundamental factors that affect both the contact between the bone and the implant and the overall integration. Mechanical forces, such as compression and tension, have an impact on the integrity of the BII, while biological factors, including bone quality and growth factors, play a crucial role in orchestrating the healing process. Molecular mechanisms, involving cells like osteoblasts and osteoclasts, as well as signaling molecules, are essential for the process of osseointegration. Additionally, cell therapies, particularly Mesenchymal Stem Cells (MSCs) and Platelet-rich Plasma (PRP) show promise in enhancing the healing of the BII. these factors and exploring innovative techniques are of utmost importance for improving the outcomes of implant procedures and enhancing patient care in the field of implant dentistry. Continued research in these areas is set to advance our knowledge of osseointegration and its optimization, ultimately shaping the future of implantology.

Keywords: Osseointegration, Bone-implant interface, bone healing

1. Introduction

The bone-implant interface is the area where a foreign object, such as an implant, contacts the bone. This is critical for successful implant integration and healing(1,2). Once the implant is embedded in the bone, the body begins to heal the area by embedding the implant into the surrounding bone tissue(3). The biomechanical properties of the bone-implant interface are important for implant stability. Good bone healing ensures direct implant-to-bone contact and stability (4). The contact surface between bone and implant is a heterogeneous area and is composed of many different types of tissue. This heterogeneity affects implant integration and stability (5). Morphological studies have demonstrated the presence of a fiber-free communication zone at the bone-implant interface. This region resembles the cementitious network and lamina propria found at natural bone interfaces (6).

Several factors influence the formation of a proper bone-implant interface. These factors include implant design, implant surface finish, and mechanical forces acting on the implant (7). Compression maintains the integrity of the bone-implant interface, but tension and shear forces can disrupt the interface (8).

cementitious lines and restrictive sheets found at the natural bone interface. Several factors influence the formation of an appropriate bone-implant interface, including implant design, implant surface properties, and mechanical forces acting on the implant. Compression maintains the integrity of the bone-implant interface, while tension and shear forces can disrupt the interface (1,9). The contact between the bone and the implant is critical for implant integration and long-term stability. Researchers can enhance patient outcomes by better understanding the elements that influence bone-implant contact. Many factors influence the effectiveness of the bone-implant relationship. The biomechanical features of the bone-implant interface (BII), which determine implant stability, are the most notable of these factors (4). These attributes include bone density, the ability of bone to withstand stress, bone density, and contact with the implant. The quantity of bone remaining after extraction influences implant width and length selection, impacting surface area and bone-to-implant contact (5). The contact surface between a bone and an implant can be impacted by implant-related characteristics, such as handling surfaces and coatings, despite research showing that implant design and surface features have little impact on this surface. According to several research, increasing the contact surface can enhance implant and bone integration (7).

The bone-implant interface (BII)

Implant surface treatment can be an important factor in promoting successful bone integration by improving bone-implant contact (BIC) and stimulating bone formation and healing(8). By changing the topography of the implant surface, surface treatments such as acid etching, sandblasting, and plasma blasting can create a harder surface that increases the surface area of the implant, promotes BIC, and improves the bone integration process (8,9). The implant coating can also affect the BIC by altering the surface chemistry of the implant (6). For example, hydroxyapatite (HA) coatings can promote bone integration by mimicking the natural mineral composition of bone and improving BIC (8,9). The implant surface treatment can also affect the bioreactivity of the surrounding bone tissue. Surface treatments that create a harder surface can stimulate the production of growth factors and cytokines that promote bone formation and healing. However, it is important to note that the effectiveness of the surface treatment on the BIC may depend on the type of implant material used. For example, surface treatments that improve bone integration in titanium implants may not have the same effect on other materials such as zirconia (8).

Different types of implant surface treatments:

The implant surface can be treated in a variety of ways to improve bone integration and long-term clinical outcomes. The specific treatment used varies depending on the type of implant and the desired outcome (10,11). A mechanical treatment that uses grinding, sanding, or machining to produce a harder or smoother surface. Surface sandblasting is a common mechanical treatment to produce a harder surface on titanium dental implants (12). Chemical treatments change the roughness, composition, and surface energy of the implant surface. They are made using acids, alkalis, sol-gels, anodizing, and other methods (10). Alumina (Al2O3), TPS (titanium plasma spray), and hydroxyapatite spray are common chemical treatments used for dental implants (13). Physical treatment methods include plasma injection and ion deposition. Plasma spraying involves depositing a coating on the implant surface using a plasma jet, while ion deposition involves bombarding the implant surface with ions to change its properties (10).

biomaterials, molecules, and drugs have been coated on dental implants

In the pursuit of enhancing the efficacy of dental implants, various materials have been employed as coatings. These materials encompass bioavailable calcium phosphate (Ca-P), bioactive ceramics, peptides, antibiotics, and silver nanoparticles. The biomimetic Ca-P coating, for instance, replicates the inherent mineral composition of bone, potentially prompting bone formation and the healing process. (14). They have been used as carriers of bone-building proteins, growth factors, and antibiotics. Bioactive ceramics such as hydroxyapatite and tricalcium phosphate are commonly used as encapsulation materials in dental implants due to their ability to form bonds between the implant surface and surrounding bone tissue (15). Peptides have been proposed as a bioactive coating to the implant surface, especially the transmucosal part, to facilitate the attachment of various host cells(16). In the pursuit of enhancing the efficacy of dental implants, various materials have been employed as coatings. These materials encompass bioavailable calcium phosphate (Ca-P), bioactive ceramics, peptides, antibiotics, and silver nanoparticles. The biomimetic Ca-P coating, for instance, replicates the inherent mineral composition of bone, potentially prompting bone formation and the healing process(5,14). Various drugs have been applied to dental implants to promote bone healing and prevent implant failure. These drugs include bisphosphonates, growth factors, and anti-inflammatory agents(17). Bioactive coatings can enhance the performance of dental implants by facilitating the formation and healing of bone tissue at the interface between the implant and the bone. This can increase the stability and longevity of the implant (14,16).

Mechanical factors: loading and stress

The bone-implant interface (BII), essential for optimizing implant success and long-term stability, can be strongly influenced by various mechanistic variables. When selecting the best implant designs, surgical procedures, and surface treatments, surgeons and implant designers should take these considerations into account(6). The distribution of load and stress is crucial for the bone to integrate well with the implant and ensure its long-term function. The contact surface can be damaged or displaced by tensile and shear forces, while compression forces help to preserve the bond between the bone and the implant. (8). Bone remodeling and implant fit are highly dependent on load and mechanical stress (4). The bone around the implant can grow and regenerate more quickly with appropriate bone load (18). However, high or irregular loads can lead to implant failure or bone resorption(6). Initial implant stability, or the initial mechanical fixation achieved during implant placement, is affected by load and tension. For bone integration and the long-term success of the implant, sufficient initial stability is required (18). The retention of the implant at BII is influenced by mechanical factors such as friction and mechanical locking. The stability and integration of the implant can be affected by the surface roughness of the implant, which alters these surface phenomena (4).

The bone-implant interface (BII) responds to mechanical loading:

When the implant is loaded, it puts pressure and tension on the surrounding bone. These stresses and strains stimulate the bone to reshape or rebuild itself to better withstand the load. The bone-implant interface (BII) responds differently to different types of mechanical loads. The phenomenon of friction between the implant surface and the bone tissue is used to maintain the shear load at the BII level. These phenomena contribute to implant retention at BII and may affect implant stability and integration (4). The deformation and stiffness properties of materials used in implant dentistry, especially implant materials, can affect communication tissues (8). Loads applied to the dental implant can cause deformation of the implant and surrounding tissues, possibly initiating remodeling activity (19). The design of the implant thread can affect the stress distribution at BII. Using finite element analysis, the researchers evaluated the microscopic movement pattern inside the implant and surrounding bone with different thread designs (17). The results show that all micro-motions are located near the surface between cortical and cancellous bones, and the square thread section has the most favorable micro-motion value(8). The implant diameter and length affect the stress distribution of BII by increasing the contact area ratio [35]. This may lead to a more uniform distribution of stresses and strains at the BII, thereby promoting successful bone integration (20). Loading the implant too soon or too late before the bone forms a regular structure can have negative biological consequences. If the load is applied too early, the bone density and stability around the implant can decrease. If the load is delayed too much, the bone can be absorbed or the implant can fail (8).

Biological factors play a crucial role in BII:

The status of the host bone bed, including its intrinsic biological factors, influences the success of the BII(21). Factors such as bone quality, vascularity, and the presence of any underlying diseases or conditions can affect the integration and healing process (22). Bone healing around implants involves a cascade of cellular and extracellular biological events that take place at the BII until the implant surface is finally covered with newly formed bone (1). These biological events include the activation of osteogenic processes similar to those of the bone healing process, at least in terms of initial host response (21,13,17,5). The cascade of biological events at the BII is regulated by growth and differentiation factors released by the activated blood cells at the BII (22). These factors enhance osseointegration by promoting bone formation and healing(5). Implant-related factors such as implant design, surface treatment, and coatings can also affect the BII by altering the surface topography, composition, and surface energy of the implant (8). For example, surface treatments that create a rougher surface can stimulate the production of growth factors and cytokines that promote bone formation and healing (22). Most of the important signaling molecules that are involved in bone healing surrounding implants are Transforming growth factor-beta (TGF-β), Bone morphogenetic proteins (BMPs), Platelet-derived growth factor (PDGF), Insulin-like growth factor-1 (IGF-1), Vascular endothelial growth factor (VEGF) (23).

The molecular mechanism of bone healing

The interface between bone and implants involves various cellular and molecular processes. The material and surface properties of the implant may affect the specific molecular mechanisms of bone healing at the bone–implant interface. To optimize osseointegration and improve implant outcomes, it is important to understand these cellular and molecular phenomena. This will help to develop strategies to increase the success rate of the implants (12,24). The interface between bone and implants involves various cellular and molecular processes. The material and surface properties of the implant may affect the specific molecular mechanisms of bone healing at the bone–implant interface. To optimize osseointegration and improve implant outcomes, it is important to understand these cellular and molecular phenomena. This will help to develop strategies to increase the success rate of the implants (16). The bone-implant interface undergoes various cellular reactions during the healing process. These reactions involve the interactions between the cells that make bone (osteoblasts), the cells that break down bone (osteoclasts), and other immune cells. These cellular responses help to reshape and adjust the bone tissue around the implant. Growth factors and cytokines are molecular signaling pathways that mediate the communication and regulation of bone healing among cells. These signaling molecules have important roles in attracting, differentiating, and activating osteocytes at the bone-implant interface (13). Osseointegration is the direct structural and functional connection between the implant and the surrounding bone. The molecular mechanisms underlying osseointegration involve the formation of a mineralized tissue interface between implant and bone mediated by cellular and molecular events(24).

Cell therapy at the bone-implant interface

Cell therapy is a promising approach to promote bone healing at the bone-implant interface (BII). Here are some key takeaways from the search results. The goal of current implant research is the development of devices that provide controlled, directed, and rapid healing (6). Cell therapy is one approach being investigated to improve bone healing in BII [39]. Mesenchymal stem cells (MSCs) are a type of cell therapy being investigated to improve bone healing in BII (25). Bone regeneration can be enhanced by MSCs, which can turn into osteogenic cells. Another cell therapy that can improve bone healing in BII is PRP, which has growth factors and cytokines that boost bone formation and healing. Biological processes can change and affect osseointegration in BII, which can reduce the long-term success of implants. Cell therapy can improve osseointegration and implant success rates. Clinical studies are testing the use of cell therapy to enhance bone healing in BII. For example, one study examined the effects of using one’s own bone marrow MSCs and PRP on bone regeneration and osseointegration in titanium implants coated with hydroxyapatite. This study showed that MSCs and PRP together improved bone regeneration and osseointegration more than controls (25). PRP together improved bone regeneration and osseointegration more than controls (25).

Morphological studies

Osseointegration, which is essential for the clinical success of dental implants, is assessed by criteria such as stability, function, and maintainability, often as assessed by quantitative analyses of dental implants' direct bone-implant interface (BI1). Since Brånemark introduced the concept of bone integration in 1977, the measurement of the ratio of BIC on uncalcified histological sections by optical microscopy has been considered as the reference method of analysis(26,19). The implanted bone needs to be prepared and stained before it can be analyzed by histomorphometry. This method is not only tedious but also prone to errors that can ruin the sample. Histomorphometry only gives a two-dimensional view of the bone, which may not reflect the true situation. A three-dimensional analysis can provide a more accurate picture of the bone structure. Recently, micro-computed tomography (μCT) has emerged as a potential alternative method to evaluate the morphology and 3D architecture of BICs. This rapid and non-destructive method not only provides information on 3D structures but can also be used to evaluate quantitative parameters such as bone density (20). Given the limitations of this animal model study, 3D-μCT can be used to analyze bone and implant surfaces to complement morphometric measurements. 3D-μCT analysis may even outperform histomorphometry in that it allows full visualization of implant and bone morphology while eliminating random variables caused by directional cutters (27).

Discussion:

The quality of the bone-implant interface (BII) is essential for the successful healing and integration of implants. It affects the stability of the implant and the long-term outcomes of the treatment (30-31). In this discussion, we will explore the different factors that influence the BII, such as the design and surface of the implant, the mechanical and biological factors, the molecular mechanisms, and the potential of cell therapy. The design and surface of the implant are important factors that affect the bone-implant interface. The implant needs to have a good contact surface with the bone for integration. The contact depends on factors like the width, length, and surface area of the implant. Studies have shown that changing the surface properties of the implant, such as by acid etching or hydroxyapatite coatings, can improve the bone-implant contact and help the bone integration process. These treatments make the environment more favorable for bone healing and formation(10). To enhance bone integration, various surface treatments have been applied to implants. These treatments can be mechanical, chemical, or physical, and they affect the surface in different ways. For example, mechanical treatments like sandblasting make the surface harder, chemical treatments like acid etching change the surface roughness and composition, and physical treatments like plasma deposition modify the surface properties. Depending on the implant type and the expected outcome, different treatments can be chosen. For instance, surface sandblasting is often used for titanium dental implants to improve integration (28). Biological factors are fundamental in determining the success of the bone-implant interface. Bone quality, vascularity, and underlying medical conditions can all impact integration and healing (22). Bone formation and healing are influenced by the biological events that occur at the BII, which are driven by growth and differentiation factors. These factors include TGF-β, BMPs, PDGF, IGF-1, and VEGF, which help with osseointegration (23).

Understanding the molecular mechanisms involved in bone healing at the BII is essential for optimizing osseointegration. Osteoblasts, responsible for bone formation, are influenced by the implant surface and microenvironment, promoting bone deposition around implants. Cellular responses, including interactions between osteoblasts and osteoclasts, contribute to the remodeling and adaptation of peri-implant bone tissue. Molecular signaling pathways, such as growth factors and cytokines, play a vital role in osteocyte recruitment, differentiation, and activity at the BII(12,14). Cell therapy, particularly the use of Mesenchymal Stem Cells (MSCs) and Platelet-rich Plasma (PRP), is a promising avenue for enhancing bone healing at the BII. MSCs can differentiate into osteogenic cells, stimulating bone regeneration. PRP, containing growth factors and cytokines, promotes bone formation and healing. Clinical studies have shown promising results in using cell therapy to improve bone regeneration and osseointegration around dental implants (25,29). Traditionally, histomorphometric analysis has been used to assess osseointegration, but it has limitations in terms of time-consuming procedures, potential damage to samples, and two-dimensional representations. Micro-computed tomography (μCT) has emerged as an alternative method, providing rapid, non-destructive 3D analysis of BII. μCT not only offers insights into 3D structures but also enables quantitative evaluation of bone density. This method can overcome the limitations of histomorphometry, offering a more accurate representation of implant and bone morphology (26,27).

Conclusion

In conclusion, the bone-implant interface is a critical factor for the success of implant integration and long-term stability. Implant design, surface treatments, mechanical loading, biological factors, molecular mechanisms, and cell therapy all play significant roles in influencing the BII. Understanding these factors and exploring innovative techniques can contribute to improved implant outcomes, better patient care, and enhanced clinical success in implant dentistry. Further research in these areas will continue to advance our understanding of osseointegration and its optimization.

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