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Enhancing Osseointegration: The Impact of Implant Surface Roughness- A Narrative Review

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Abstract

When implantology first started, the techniques intended to treat patients were divided into two operational periods, separated between four to six months. Dental implants may now be loaded and inserted during the same surgical process. Improvements in surgical technique, changes in implant design, superior implant manufacturing quality, innovations in surgical equipment quality, meticulous patient screening, and proper implant surface treatment are some of the reasons for this shift. The clinical findings demonstrate that treating at-risk patients and minimizing healing time depend on proper surface treatment. It is possible to greatly enhance the surface characteristics of dental implants during the manufacturing process, as well as during the loading of the dental implants into the osteotomy site which will impact the activity of cells during the healing phase and ultimately influence the host tissue response—a crucial prerequisite for clinical success. Numerous studies have demonstrated the significance of these surface modifications in enhancing implant effectiveness. To create a microporous structure with nanoscale architecture, enhanced bioactivity, hydrophilicity, and antibacterial qualities, a number of methods have been proposed to alter the implant surface topography and surface chemistry. The various surface types of dental implants and their effects on osseointegration are the main topics of this review.

Keywords: Dental implant, Surface coating, Surface modification, Surface topography.

INTRODUCTION

Dental implants have become a dependable treatment option for oral rehabilitation in patients who are partially or fully edentulous, offering a secure foundation for various types of prostheses. They are now a standard procedure for replacing a missing teeth, offering numerous benefits, but also presenting challenges, particularly with discerning patients. Over 45 years ago, Brånemark and colleagues first described the process of osseointegration [1], marking the beginning of a new era in the study of dental implant design and materials. While their work initially focused on implant geometry, recent biomedical research has shifted its focus towards the osteoinductive properties of implant surfaces.

With differences in dimensions, bulk and surface materials, thread designs, implant-abutment connections, surface topography, chemistry, wettability, and surface modifications, it is estimated that there are currently around 1,300 different implant systems available [2]. Commonly observed implant shapes include tapered and cylindrical forms [3]. Surface characteristics, such as topography, wettability, and coatings, play a crucial role in the biological processes during osseointegration by facilitating direct interaction with host osteoblasts during bone formation [4].

Dental implants generally have high long-term success rates. However, it's important to recognize that a small percentage of patients do experience implant failures. Primary implant failure, affecting 1-2% of patients within the first few months, is usually caused by insufficient osseointegration [5]. Secondary implant failure, which can occur several years after successful osseointegration, is often due to peri-implantitis and affects around 5% of patients [6]. The demographic shift in industrialized countries have resulted in a growing number of elderly patients with complex clinical issues, such as reduced bone quality or quantity and other challenging comorbidities. Conditions like diabetes mellitus, osteoporosis, bisphosphonate use, or prior

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radiotherapy can hinder osseointegration in these patients. This makes them particularly challenging in the field of dental implantology, emphasizing the need for bioactive surface modifications that can enhance osseointegration after implant placement [7]. Additionally, the goal of developing new bioactive surface properties is to speed up osseointegration, allowing for more convenient early loading protocols. This article offers an overview of dental implant surface modifications and structures, as well as commercial surface treatments, techniques for assessing dental implant surfaces, and potential structural alterations that may occur after implant placement.

OSSEOINTEGRATION

"A direct structural and functional connection between ordered, living bone and the surface of a load-carrying implant" was the original phrase to describe osseointegration as presented under a light microscope [8]. An alloplastic substance that is rigidly fixed in bone during functional stress, as hypothesized by Zarb and Albrektsson, can be described more clinically as an asymptomatic process [9].

The process of creating an osteotomy site for implant placement causes trauma to the bone tissue, which is then followed by numerous phases of wound healing. The first outcomes of the cellular and plasmatic hemostasis systems are fibrin polymerization and the creation of a blood clot. The blood clot serves as a framework for the deposition of extracellular matrix (ECM), neo-angiogenesis, and bone-forming cells [10]. The cell adhesion mechanism involves a multitude of sticky proteins, including fibronectin, vitronectin, osteopontin, fibrinogen, and thrombospondin. The tripeptide arginine-glycine-aspartic acid, which is recognized by integrin receptors on the cell surface, is present in all of these proteins [11].

Contact osteogenesis occurs when osteogenic cells on the implant's surface produce new bone, when the new bone generates from the borders of the drill hole is called distant osteogenesis. Distance osteogenesis is the process by which osteoblasts move to the implant cavity's surface, differentiate, and help create new bone. As a result, the bone develops appositionally along the direction of the implant. In contact osteogenesis, de novo bone is created by osteogenic cells migrating directly onto the implant surface [12]. The amount of new bone growth at the bone-implant contact has a major impact on a dental implant's secondary stability. Following Wolff's Law, load-oriented bone remodeling takes place, resulting in realigned lamellar bone replacing the main woven bone. The purpose of this procedure is to transfer mechanical impulses to the neighboring bone and maximize occlusal load absorption. Approximately 60–70% of the implant surface is covered in bone by the time the remodeling period is finished [13]. According to the theory of mechanotransduction, a person's bone remodeling continues to occur throughout their lifetime. The development of novel implant surface topographies to promote osteoblast migration, adhesion, proliferation, and differentiation has been the focus of recent research efforts [14].

SURFACE MODIFICATION OF DENTAL IMPLANT

Surface modifications of dental implants can be classified into macro-, micro-, and nano-roughness [15].

Macro roughness material has a millimeter to micron range. This scale is closely connected to the implant shape, which includes threaded screw and macro porosity. Through the mechanical interaction of the rough surface imperfections and the bone, a suitable macro roughness can directly increase the initial stability of the implant and its long-term fixation [16].

Micro roughness typically falls between one and ten microns. Junker et al. emphasized that optimum surface topography at the micron level leads to better bone development and interlocking at the implant interface [2].

Nano roughness materials ranging in size from 1 to 100 nm are used on the implant surface. It is thought that this tiny roughness enhances osseointegration by encouraging protein absorption and osteoblast adhesion [17]. A more textured surface topography at the nanoscale raises the surface energy, which in turn improves the surface's wettability to blood and cell adhesion. Through the acceleration of wound healing, nanotopography can facilitate the processes of cell differentiation, migration, and proliferation, ultimately improving osseointegration after implant surgery [18]. The most popular techniques for producing nanoscale topography are grit blasting, ionization, and acid etching. Research has indicated that surfaces grit-blasted with biphasic calcium phosphate can facilitate osseointegration more quickly than smooth surfaces. Calcium phosphate coatings can also promote osseointegration by the use of plasma spraying, biomimetic, and electrophoretic deposition. The process of electrochemically depositing calcium phosphates from saturated solutions releases calcium and phosphate ions from these coatings, which aid in the precipitation of biological apatite nanocrystals upon the incorporation of different proteins. This, in turn, facilitates osteoblast differentiation, cell adhesion, and the synthesis of mineralized collagen, the extracellular matrix of bone tissue. In order to form bone tissue, osteoclast cells must first absorb calcium phosphate coatings. This promotes direct bone-implant contact without the need for a connective tissue layer, which results in the biomechanical fixation of dental implants [19].

Methods for improving the surface of dental implants:

Mechanical method: The surfaces produced by grinding, blasting, machining, and polishing can be smooth or rough, which can enhance cell adherence, proliferation, and differentiation [20].

Chemical method: To modify the surface roughness and composition and increase surface energy, chemical surface modification techniques include anodization, chemical vapour deposition, sol gel, hydrogen peroxide treatment, and chemical treatment with acids or alkali [21].

Physical methods: Physical techniques for implant surface modification include sputtering, ion deposition, and plasma spraying. Vacuum and atmospheric plasma spraying are examples of plasma spraying techniques. Sputtering is one way to apply thin coatings on implant surfaces, and it is thought to enhance mechanical and biological characteristics.

TECHNIQUES FOR TITANIUM IMPLANT SURFACE TREATMENT

SANDBLASTED ACID ETCHING

By applying high-velocity abrasive particles, such as titanium oxide or alumina, to the implant surface, sandblasting produces an observable macro-roughened texture. Through efficient contamination removal and surface area enhancement, this procedure promotes mechanical interlocking with surrounding bone for enhanced initial stability and a strong bone-implant contact. However, acid-etching modifies the titanium oxide layer at the microscopic level by using acidic solutions like sulfuric or hydrochloric acid, producing a textured surface with pits and imperfections. This surface has been microroughened to increase bioactivity, which in turn promotes protein adsorption and makes it easier for osteogenic cells—which are necessary for osseointegration—to adhere and proliferate. Combining these methods yields improved macro- and micro-roughness on dental implants, which together maximize the biological response. Improved clinical results in implant dentistry are the final result of this dual strategy, which supports both short-term stability and long-term bone integration [22].

HYDROPHILIC IMPLANTS

Normal titanium implants have low surface energy and are hydrophobic due to their absorption of carbonates and hydrocarbons from the air. Implants are hydroxylated, cleaned under nitrogen, and kept in isotonic saline until needed in order to combat this. Nanoscale chemical changes provide a hydrophilic surface with a high surface energy, improving the absorption of oxygen and lowering the carbon content. Applying a hydroxide ion solution, for example, increases hydrophilicity and surface energy. In animal and human trials, implants treated with SLActive® exhibit increased hydrophilicity and surface energy, which promotes protein affinity, cell adhesion, and osteoblast activity—all important for the early phases of osseointegration.3. By attracting hydrophobic bacteria such as P. gingivalis, A. actinomycetemcomitans, and F. nucleatum, hydrophilic surfaces prevent bacterial adherence and may enhance implant hygiene and long-term biofilm formation prevention [23].

HYDROXYAPATITE

Enhances the osteoconductive qualities of titanium implants by covering them with a substance that provides essential calcium and phosphate for bone growth. HA particles are heated and deposited into the implant surface under regulated conditions during the plasma spraying process, which is the most popular method of applying nano-HA. In normal circumstances, the HA layer should be 40–50 µm thick. Other spray parameters that may be changed include gas mixture, flow rate, and power. In difficult bone types like grafted or type IV bone, clinical research indicates that implants coated with HA accelerate bone integration. Fluoridated hydroxyapatite that has been electrochemically deposited may also be beneficial against certain bacteria. Studies on osteointegration and microbiological contamination between HA-coated and uncoated implants are yielding inconsistent findings, therefore long-term stability and clinical consequences are yet unknown. Failures of the HA covering to adhere to the implant may also give rise to concerns about peri-implant tissue problems and bacterial microleakage. For dental implantology, more investigation is required to properly evaluate the effectiveness and dependability of HA coatings [24].

PLASMA SPRAYING

Titanium powders are introduced into a plasma torch with a high temperature using this approach. The titanium particles undergo melting and fusion into the implant surface as a result of the intense heat generated by the torch. As a consequence, an average roughness of around 7 µm is obtained for the titanium plasma-sprayed (TPS) layer. Enhancing the implants' osseointegration capability, the coating technique efficiently enhances the implants' surface area [23].

CALCIUM CHLORIDE TREATMENT

The $CaCl_2$-treated titanium (Ca-HT) surface exhibits enhanced osseointegration and a superior soft tissue seal when titanium is hydrothermally treated with calcium chloride (CaCl2). By increasing osteopontin and laminin-332 adsorption, this therapy encourages osteoblast adhesion. Furthermore, it has been discovered that titanium surfaces treated with Ca-HT exhibit enhanced adhesion of fibroblasts and gingival epithelial-like cells. Crucially, it is shown that the Ca-HT treatment has no effect on bacterial adhesion, namely *S. gordonii*, indicating that it improves cell adherence without raising bacterial attachment. It is postulated that calcium on titanium surface modifies saliva-acquired pellicle composition, enhancing titanium's biocompatibility while inhibiting bacterial adherence.

ANODIZATION

An electrochemical procedure called anodization is used to cover the implant surface with a thick coating of oxide. This layer increases the surface's bioactivity while also strengthening corrosion resistance. Anodized surfaces have tiny roughness increases that can enhance cell adhesion and growth [24].

PLATELET RICH PLASMA AND PLATELET RICH FIBRIN

Growth factors that can promote osteoblast adhesion and increase bone repair can be found in platelet-rich fibrin (PRF) and platelet-rich plasma (PRP) reservoirs. Pre-implantation PRP combined with autogenous bone or organic bone substitutes at the implant site produces good functional and cosmetic results, according to clinical research. Regarding implant surface modification, in vitro studies reveal that titanium surfaces co-treated with zoledronic acid and PRF enhance the number and length of filopodia in adhering osteoblasts in comparison to surfaces treated with zoledronic acid alone. It appears that PRP and PRF could improve the main stability and early bone development of dental implants. This would be especially helpful for patients receiving bisphosphonate medication. But there is still debate over the relative efficacy of PRF and PRP in promoting osteogenic cells [25].

BIOACTIVE CERAMIC COATING

Coatings enhanced with calcium and phosphorus have drawn the most attention among all engineering-based surface modifications for orthopedic and dental implants. These elements are crucial to the structure of natural bone, and different industrial techniques make it easier to apply them to implant surfaces. Most bio-ceramic coatings that are sold commercially, such Plasma Sprayed Hydroxyapatite (PSHA), have a thickness of between 20 and 50 µm. For PSHA coatings to maintain physical integrity throughout implant insertion and operation, grit-blasted or etched metal surfaces must mechanically interlock with the ceramic-like biomaterial. PSHA-coated implants had better early bone bonding and bone-to-implant contact, according to studies. Concerns regarding consistent deterioration over time and decreased mechanical qualities at the bone-coating interface, however, have caused them to lose popularity in dental practice [26].

PHOTOFUNCTIONALIZATION

By changing the hydrophilicity of the TiO_2 layer, UV treatment, also known as photofunctionalization, improves the osteoconductivity of the titanium implant surface. Particularly, UVA (320–400 nm) and UVC (200–280 nm) radiation can improve osteogenic cell adhesion and proliferation as well as plasma protein adsorption by making the titanium surface more hydrophilic. It has been discovered that during the early stages of osseointegration, this change mostly facilitates the formation of bone. Additionally, photofunctionalization has been demonstrated to have antibacterial properties by preventing the development of biofilms [27]. In contrast to increasing cellular metabolic activity, such as bone cell proliferation and differentiation, Del Curto et al. demonstrated that anodized-heat-treated titanium followed by UV radiation treatment demonstrated a decrease in the adhesion of *S. mutans*, *S. salivarius* and *S. sanguis* [28].

PHARMACEUTICAL COATINGS

Antibiotic coatings (such as bacitracin, amoxicillin, doxycycline, and gentamycin) applied to the surfaces of dental implants may chemically enhance cellular and molecular responses, minimize infection rates, and accelerate osseointegration [29]. Adding doxycycline to implant surfaces might regulate the rate of release on the implant site because it is one of the antibiotics that is frequently used to prevent infection following implant surgery [30].

On a titanium surface, Nichol et al. created a single-layered sol-gel coating that was loaded with gentamicin and examined its effectiveness against strains of Staphylococcus bacteria. Being a broad-spectrum antibiotic, gentamicin is effective against both Gram-positive and Gram-negative bacteria. 99% of the gentamicin in the coating was eluted 48 hours after the Minimum Inhibition Concentration (MIC) was reached in

1 hour, and all identified Staphylococcus variations were eradicated 24 hours later. Although the author found these results good, the antibiotic release was too rapid for long-term protection, making them not the best covering for dental implants [31].

Applying vitamin D to the surface of dental implants has a strong biological effect on osseointegration. Osteoblasts with vitamin D-responsive receptors directly alter cellular functions by regulating gene expression. Vitamin D modulates these receptors, which work in tandem with important proteins necessary for bone production, such as osteocalcin, and hence contribute significantly to bone health [32]. The topical use of vitamin D during immediate implant operations may have a negligible impact on osseointegration, according to controlled animal research by Salomo-Coll et al. However, crestal bone loss was significantly reduced and bone-to-implant contact increased by around 10% in dental implants treated with topical vitamin D [33].

Due to their potential to improve osseointegration, statin medications—which are frequently recommended for cholesterol management—have attracted attention in the field of dental implantology. By increasing the production of bone morphogenetic protein-2 (BMP-2), a crucial regulator of bone metabolism and regeneration, statins have been shown to support bone growth. According to research done by Jun et al., in a rabbit model, local treatment of simvastatin in a 25 mm dose applied as a gel around dental implants greatly enhanced bone-implant contact by 20% as compared to control groups [34].

CONCLUSION

An innovative device called a dental implant is used to replace lost teeth and return function and look as near to natural as feasible. Understanding the intricate nature of dental implants is crucial for the dentist. The best techniques for drilling and inserting implants should also be known to surgeons, as any potential alterations in the structure of the implant that could take place. The success and survival rates of dental implants will be increased with the use of this knowledge.

Conflicts of Interest

The author reports no conflicts of interest.

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