Review Article

Implant considerations and surface modifications – A literature review

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ABSTRACT

Dental implants represent a reliable treatment option in oral rehabilitation of partially or fully edentulous patients to secure various kinds of prostheses. Dental implants have become a standard procedure for single tooth replacement not only in the esthetic zone, providing many advantages but also challenges in sophisticated patients. The process of osseointegration was reported more than 45 years ago. However, it was not until the last decade that the focus of biomedical research shifted from implant geometry to the osteoinductive potential of implant surfaces. Surface characteristics such as topography, wettability, and coatings contribute to the biological processes during osseointegration by mediating the direct interaction to host osteoblasts in bone formation.

KEY WORDS: Implant, Osseointegration, Surface coatings, Surface modifications

INTRODUCTION

Nowadays, dental implants represent a reliable treatment option in oral rehabilitation of partially or fully edentulous patients to secure various kinds of prostheses. Dental implants have become a standard procedure for single tooth replacement not only in the esthetic zone, providing many advantages but also challenges in sophisticated patients.

Brånemark *et al.*, first described the process of osseointegration more than 45 years ago.[1,2] Their work launched a new era of research on shapes and materials of dental implants. However, it was not until the last decade that the focus of biomedical research shifted from implant geometry to the osteoinductive potential of implant surfaces.

Today, roughly 1300 different implant systems exist varying in shape, dimension, bulk and surface material, thread design, implant-abutment connection, surface topography, surface chemistry, wettability, and surface modification.[3] The common implant shapes are cylindrical or tapered.[4] Surface characteristics such as topography, wettability, and coatings contribute to the biological processes during osseointegration[5] by mediating the direct interaction to host osteoblasts in bone formation.

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OSSEOINTEGRATION OF DENTAL IMPLANTS

Osseointegration of dental implants was previously characterized as a structural and functional connection between newly formed bone and the implant surface, which became a synonym for the biomechanical concept of secondary stability.[6-12] Osseointegration comprises a cascade of complex physiological mechanisms similar to direct fracture healing. The drilling of an implant cavity resembles a traumatic insult to bony tissue leading to distinct phases of wound healing.[13] Initially, mechanisms of cellular and plasmatic hemostasis lead to fibrin polymerization and the formation of a blood clot, which serves as a matrix for neoangiogenesis, extracellular matrix deposition, and invasion of bone-forming cells.[3,14] New bone generates from the borders of the drill hole (distance osteogenesis) or by osteogenic cells on the surface of the implant (contact osteogenesis). In distance osteogenesis, osteoblasts migrate to the surface of the implant cavity, differentiate, and lead to the formation of new bone. Thus, bone grows in an appositional manner toward the implant. In contact

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osteogenesis, osteogenic cells migrate directly onto the implant surface and generate *de novo* bone.[3]

The secondary stability of a dental implant largely depends on the degree of new bone formation at the bone-to-implant interface.[15] According to Wolff's Law, the subsequent phase of load oriented bone remodeling leads to a replacement of primary woven bone to realigned lamellar bone to optimize the absorption of occlusal load[3,14] and to transmit the mechanical stimuli to the adjacent bone.[14] At the end of the remodeling phase, about 60–70% of the implant surface is covered by bone.[16] This phenomenon has been termed bone-to-implant contact and is widely used in research to measure the degree of osseointegration.[16] According to the concept of mechanotransduction, bone remodeling continues lifelong.[14] Research efforts have been focused on designing novel topographies of implant surfaces to optimize osteoblastic migration, adhesion, proliferation, and differentiation.

STAGES OF OSSEOINTEGRATION

Direct bone healing, as it occurs in defects, primary fracture healing, and in Osseointegration is activated by any lesion of the pre-existing bone matrix. When the matrix is exposed to extracellular fluid, noncollagenous proteins and growth factors are set free and activate bone repair.[17] Once activated; osseointegration follows a common, biologically determined program that is subdivided into three stages:

- Incorporation by woven bone formation;
- Adaptation of bone mass to load (lamellar and parallel fibered bone deposition);
- Adaptation of bone structure to load (bone remodeling).

MORPHOLOGICAL SURFACE MODIFICATION

By increasing the surface roughness, an increase in the osseointegration rate and the biomechanical fixation of titanium implants have been observed. The implant modifications can be achieved either by additive or subtractive methods. The additive methods employed the treatment in which other materials are added to the surface, either superficial or integrated, categorized into coating and impregnation, respectively. While impregnation implies that the material/chemical agent is fully integrated into the titanium core, such as calcium phosphate (CaP) crystals within titanium oxide (TiO_2) layer or incorporation of fluoride ions to surface, the coating on the other hand is addition of material/agent of various thicknesses superficially on the surface of core material. The coating techniques can include titanium plasma spraying (TPS), plasma-sprayed hydroxyapatite (PSHA) coating, alumina (Al_2O_3) coating, and biomimetic CaP coating. Meanwhile, the subtractive techniques are the procedure to either remove the layer of core material or plastically deform the superficial surface and thus roughen the surface of core material. The common subtractive techniques are large grit sands or ceramic particle blasts, acid etch, and anodization. The removal of surface material by mechanical methods involved shaping/removing, grinding, machining, or grit blasting through physical force. A chemical treatment, either using acids or using alkali solution of titanium alloys, in particular, is normally performed not only to alter the surface roughness but also to modify the composition and to induce the wettability or the surface energy of the surface. As for physical treatment such as plasma spray or thermal spray, it is often carried out on the outer coating surface to improve the esthetic of the material and its performance. In addition, ion implantation, laser treatment and sputtering, alkali/acid etching, and ion deposition are also utilized.

Turned or Machined Dental Implant Surface

The first generation of dental implants, termed the turned implants, had a relatively smooth surface after being manufactured, are submitted to cleaning, decontamination, and sterilization procedures. These surfaces are usually and inadequately called — smooth since scanning electron microscopy analysis showed that they have grooves, ridges, and marks derived from tools used for their manufacturing which provides mechanical resistance through bone interlocking. However, the main disadvantage regarding the morphology of non-treated implants is the fact that osteoblastic cells are prone to grow along the grooves existing on the surface, which in terms of clinical implications means a longer healing time required. The success rates of turned implants in challenging situations such as low bone density have been reported to be lesser than when placed in areas with good bone quality. Due to morphological characteristics and lower resistance to removal torque, machined dental implants are becoming commercially unavailable. Studies have shown lower primary stability for the turned implants; they demonstrated secondary stability values and clinical success rates similar to modified implants.

Anodic Oxidation

To alter the topography and composition of the surface oxide layer of the implants, micro- or nano-porous surfaces may also be produced by potentiostatic or galvanostatic anodization of titanium in strong acids, such as sulfuric acid, phosphoric acid, nitric acid, and hydrogen fluoride at high current density or potential. When strong acids are used in an electrolyte solution, the oxide layer will be dissolved along current convection lines and thickened in other regions which create micro- or nano-pores on the titanium surface. This electrochemical process results in increased thickness and modified crystalline structure of the TiO_2 layer. However, it is a complex procedure and depends on various parameters such as current density, concentration of acids, composition, and electrolyte temperature.

Grit-blasting

Grit-blasting consists in the propulsion toward the metallic substrate of hard ceramic particles that are projected through a nozzle at high velocity by means of compressed air and leading to different surface roughness, depending on the size of the ceramic particles. The grit-blasting technique usually is performed with particles of silica (sand), Al_2O_3, titanium dioxide or resorbable bioceramics such as CaP. Al_2O_3 is frequently used as a blasting material; however, it is often embedded into the implant surface, and residue remains even after ultrasonic cleaning, acid passivation, and sterilization. It has been documented that these particles have been released into the surrounding tissues and interfered with the osteointegration of the implants. Moreover, this chemical heterogeneity of the implant surface may decrease the excellent corrosion resistance of titanium in a physiological environment. TiO_2 particles with an average size of 25 µm can produce moderately rough surfaces in the 1–2 µm range on dental implants.

Acid-etching

The immersion of a titanium dental implant in strong acids such as hydrochloric acid, sulfuric acid, nitric acid, and hydrogen fluoride is another method of surface modification which produces micro pits on titanium surfaces with sizes ranging from 0.5 to 2 µm in diameter 40. The resulting surface shows a homogenous roughness, increased active surface area and improved adhesion of osteoblastic lineage cells 41. Dual acid-etching consists in the immersion of titanium implants for several minutes in a mixture of concentrated HCl and H_2SO_4 heated above 100°C to produce a micro-rough surface that may enhance the osteoconductive process through the attachment of fibrin and osteogenic cells, resulting in bone formation directly on the surface of the implant. These studies hypothesized that implants treated by dual acid-etching have a specific topography able to attach to fibrin, improving the adhesion of osteogenic cells, and thus, promoting bone apposition. On the other hand, acid-etching can lead to hydrogen embrittlement of the titanium, creating micro cracks on its surface that could reduce the fatigue resistance of the implants. Indeed, experimental studies have reported the absorption of hydrogen by titanium in a biological environment. This hydrogen embrittlement of titanium is also associated with the formation of a brittle hybrid phase, leading to a reduction in the ductility of the titanium which is related to the occurrence of fracture in dental implants.

Grit-blasting and Acid Etching

Following grit-blasting, the surface is submitted to acid-etching to further enhance the topographic profile of the surface and removes processing by-products. The advantages of this method include an increase in the total surface area of the implant, achieved due to the selective removal resulting from electrochemical differences in the surface topography. Nevertheless, this process should be carried out under controlled conditions, as over-etching, the surface decreases surface topography and mechanical properties and may be detrimental to osteointegration. In addition, it is important that the etching procedures following grit-blasting remove any particle remaining, because chemical analyses of failed implants have shown evidence that the presence of such particles interferes with titanium osteoconductivity regardless of the established biocompatibility profiles of the biomaterial.

Plasma-spraying

TPS consists of injecting titanium particles into a plasma torch at high temperature. These particles are projected on to the surface of the implants where they condense and fuse together, forming a film about 30 µm thick resulting in an average roughness of around 7 µm. The TPS processing may increase the surface area of dental implants up to approximately 6 times the initial surface area 46 and is dependent on implant geometry and processing variables, such as initial powder size, plasma temperature, and distance between the nozzle output and target 47. One of the major concerns with plasma-sprayed coatings is the possible delamination of the coating from the surface of the titanium implant and failure at the implant-coating interface despite the fact that the coating is well-attached to the bone tissue. In a pre-clinical study using minipigs, the bone/implant interface formed faster with a TPS surface than with smooth surface implants presenting an average roughness of 0.2 µm. However, particles of titanium have sometimes been found in the bone adjacent to these implants 48. However, while an increase of 6 times the original surface area may be a favorable scenario for bone growth and apposition it also becomes a risk factor when there is an exposure of the implant surface to the oral fluids and bacteria. In addition, a major risk with high surface roughness concerns difficulties in controlling peri-implantitis due to the intercommunication between porous regions facilitates migration of pathogens to inner bone areas, potentially compromising the success of the implant therapy.

CaP Coatings

CaP coatings, mainly composed by HA, have been used as a biocompatible, osteoconductive, and resorbable blasting materials. The idea behind the clinical use of hydroxyapatite is to use a compound with a similar chemical composition as the mineral phase of the bone to avoid connective tissue encapsulation and promote peri-implant bone apposition. For this matter, the CaP coatings disclose osteoconductive properties allowing for the formation of bone on its surface by attachment, migration, differentiation, and proliferation of bone-forming cells. In the resorbable ones, following implantation, the release of CaP into the peri-implant region increases the saturation of body fluids and precipitates a biological apatite onto the surface of the implant. This layer of biological apatite might contain endogenous proteins and serve as a matrix for osteogenic cell attachment and growth and therefore, improve osseointegration. PSHA coatings are the most commonly found among the commercially available CaP coatings. The hydroxyapatite ceramic particles are heated to extremely high temperatures and deposited at a high velocity onto the metal surface where they condense and fuse together forming a 20–50 µm thick film. This resulting surface shows enhanced bioactivity observed at early implantation times; however, the mechanical resistance of the interface between the coating and titanium is considered to be a weak point, and some cases of implant failure have been reported. Furthermore, it is recognized that regardless the resorbable blasting material, the release of particles of varied size from the surface may result in an inflammatory response detrimental to hard tissue integration. Despite the substantially for PSHA-coated implants, this type of implant has fallen out of favor in dental practice as studies have shown that coatings do not uniformly dissolve/degrade after long periods in function. Furthermore, uniform coating composition and crystallinity have not always been achieved through the plasma spray process, and the overall literature database is controversial with respect to coating composition and crystalline content in relation to the *in vivo* performance.

To improve PSHA coatings, a number of techniques have been developed with the aim of producing thin-film nanostructured bioceramic coatings, such as sol-gel deposition, pulsed laser deposition, sputtering coating techniques, electrophoretic deposition, and ion-beam-assisted deposition (IBAD). These techniques may offer a more accurate compositional control and the possibility of fabricating much thinner layers (of the order of 1 µm or less). This could be advantageous for coating stability, as the driving force for cracking and delamination decreases with decreasing coating thickness. Desirable features of thin-film coatings include coating controlled composition and thickness plus enhanced adhesion to the metallic substrate. The Sol–gel electrophoresis method can be prepared using a dip coating or a spin coating process and is capable of improving chemical homogeneity in the resulting hydroxyapatite coating as it allows for better control of the chemical composition and macrostructure of the coating. The pulsed laser deposition results in a titanium surface microstructures with greatly increased hardness, corrosion resistance, and high degree of purity with standard roughness and thicker oxide layer. The IBAD technology permits the formation of thin films at atomic and molecular levels, as well as low-temperature syntheses utilizing ionic effects. There is an increasing interest in the use of CaP in the dental implant surface coatings. However, despite having a similar composition and chemistry to that of human bone, the mechanical properties of CaP's are far from being close to those of human bone, which limits their use for load-bearing applications. Recurrent drawbacks include controlling the calcium-phosphate layer composition, resorbability, weak adhesion to the substrates, the use of high temperatures or the costs involved in the process. In fact, there are several reports of cracking and/or delamination of the coating due the generation of large thermal stresses during processing, which may affect the quality and rate of peri-implant bone formation.

Biomimetic CaP Coatings

Biomimetic coatings involve the use of microstructures and functional domains of organismal tissue function to deposit CaP on medical devices to improve their biocompatibility. This bioinspired method consists in the precipitation of CaP apatite crystals onto the dental implant surface through simulated body fluids under near-physiological or — biomimetic conditions of temperature and Ph.

CONCLUSION

In general, the long-term survival rates of dental implants are excellent. However, implant failures still occur in a small quantity of patients. Primary implant failure due to insufficient osseointegration occurs in 1–2% of patients within the first few months.[6] Secondary implant failure develops several years after successful osseointegration in about 5% of patients and is commonly caused by peri-implantitis. The demographic trend in industrialized countries consecutively leads to an increase in elderly patients with advanced clinical conditions such as impaired bone quality or quantity or other challenging comorbidities. Osseointegration might be impaired in patients with diabetes mellitus, osteoporosis, and comedication with bisphosphonates or following radiotherapy. These patients remain a great challenge in dental implantology and prompt the need for bioactive surface modifications that accelerate osseointegration after implant insertion. Besides, the aim of designing new bioactive surface properties is to accelerate osseointegration for more convenient, early loading protocols. The primary goal of biomedical research on surface modifications is to facilitate early osseointegration and to ensure long-term bone-to-implant contact without substantial marginal bone loss.

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