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Dental Implant Surface Modifications: A Review

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Abstract: *Some of the objectives for the development of implant surface modifications are to improve the clinical performance in areas with poor quantity or quality of bone, to accelerate the bone healing and thereby allowing immediate or early loading protocols and also stimulating bone growth in order to permit implant placement in sites that lack sufficient residual alveolar ridge.The goal of this review was to introduced the contemporary knowledge about the influencing factors affecting the osteointegration process of dental implants, analyze the currently available techniques for implant surface modification and their limitations, and also discuss the future trends in surface bioengineering and nanotechnology for improving the osteointegration and consequently enhance their biological performance.*
Keywords*Anodic oxidation, Grit-blasting, Acid-etching, plasma sraying, ca. sulphate coating Nanotechnology.*

I. Introduction

Constituents of dental implant and its surface treatment determine electrical charge and chemical nature of implant surface which directly influence osteoblast adhesion and protein adsorption. Currently grade 4 commercially pure titanium (cpTi) is used for endosseous implants. Grade 4 cpTi has higher strength as compared to other unalloyed available grades. Grade 5 (Ti6Al4V) is an alloyed grade specially made for dental implant procedures because of its superior fatigue properties and yield strength. HydrophilicInteraction Of Surface Of Dental Implants With Bloodproperty is influenced by chemical composition of dental implant. In light of interactions with cells, tissues and biological fluids hydrophilic surfaces are preferred over hydrophobic surfaces. [1]Surface characteristics are one of six key factors that determine the long-term success of dental implants.[2]By modifying the characteristics of the Ti surface, biocompatibility can be improved, faster osseointegration can be provoked, and the edentulous period of a patient can be finally shortened.[3-6]Some of the objectives for the development of implant surface modifications are to improve the clinical performance in areas with poor quantity or quality of bone, to accelerate the bone healing and thereby allowing immediate or early loading protocols and also stimulating bone growth in order to permit implant placement in sites that lack sufficient residual alveolar ridge. The surface characteristics at the micro or nanometre level, hydrophilicity, biochemical bonding and other features are few of the determiners which are responsible for the implant's success. [7]The surface area can be increased remarkably by using proper modification techniques, either by addition or subtraction procedures.[8-9] A surface treatment can also be classified intomechanical, chemical, and physical methods.

Implant morphology influences bone metabolism: rougher surfaces stimulates differentiation, growth and attachment of bone cells, and increases mineralization; furthermore, the degree of roughness is important. Implants may have "smooth" (machined) or roughthe literature to create implant roughness are acid etching, sandblasting, titanium plasma spraying and hydroxyapatite (HA) coating. A current tendency is the manufacturing of implants with micro and submicro (nano) topography. Furthermore, the biofunctionalization of implants surfaces, by adding different substances to improve its biological characteristics, has also been recently investigated.[10-11]This paper reviews the literature on dental implant surfaces modifications to show the current perspective of implant development

Interaction of surface of dental implants with blood

After implant placement into a prepared osteotomy , three stages of repair occur : initial formation of a blood clot occurs through a biochemical activation followed by a cellular activation and finally a cellular response. This events can be subdivided into: hemorrhage into the defect with unspecific protein, adsorption by the dental surface, platelet activation and degranulation, inflammation, recruitment, migration, and adhesion of osteogenic progenitor cells (osteoconduction), osteogenic proliferation, osteogenic differentiation withmatrix synthesis, calcification (de novo bone formation), followed by lifelong bone remodeling at the implant surface.[12] Ultimately, it culminates in either partial or complete regeneration or repair. During surgery, dental implant surfaces interact with blood components from ruptured blood vessels and within a short period of time , various plasma proteins such as fibrin get adsorbed on the material surface and the complement and kinin systems become activated.[13] The retention of these proteins by the implant surface is dependent upon the surface topography of the latter, and it is through this three-dimensional biological architecture that putative osteogenic cells migrate to the implant surface. As in fracture healing, the migration of bone cells in peri-implant healing will occur through the fibrin of a blood clot. Since fibrin has the potential to adhere to almost all surfaces, it forms and serves as a scaffold for ingrowing capillaries, collagen fibers, mesenchymal stem cells and pre-osteoblasts at the implant surface.[13] However, as the migration of cells through fibrin will cause retraction of the fibrin scaffold, the ability of an implant surface to retain this fibrin scaffold during the phase of wound contraction is critical in determining whether the migrating cells will reach the implant surface. The activation of platelets occurs as a result of interaction of platelets with the implant surface as well as the fibrin scaffold and this leads to thrombus formation and blood clotting. Platelets, however, are of considerable importance since their activation leads to a rearrangement in cell shape and to centralization of storage granules followed by the release of their contents into the extracellular environment. This process of platelet degranulation releases a number of growth and differentiation factors which play a key role in the wound healing process by acting as signaling molecules for recruitment and differentiation of the undifferentiated mesechymal stem cells at the implant surface. Plasma also contains dissolved substances such as glucose, amino acids, various ions, cholesterols, and hormones which are needed for the viability of cells and tissues.[14]

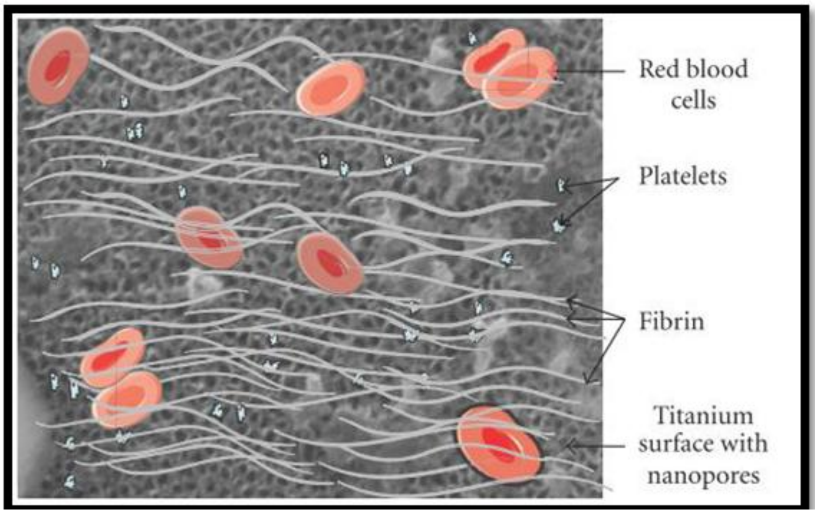


Fig no 01. Interaction of surface of dental implants with blood

These cells initially remove the necrotic debris created by the drilling process and then undergo physiological changes which lead to expression of cell surface proteins and production of cytokines and pro-inflammatory mediators.[15] This cytokine-regulated cellular recruitment, migration, proliferation and formation of an extracellular matrix on the implant surface can be influenced by the macrophages. The end result of this complex cascade is promotion of a wound healing to finally start to form de novo bone on the implant surface.

The bone remodeling phenomenon occurs through the ability of osteoblastic cells to lie down on the old bone surface or on the implant surface itself and are described as distance and contact osteogenesis. In distance osteogenesis, new bone is formed on the surface of old bone in the peri-implant site that provides a population of osteogenic cells that lay down a new matrix that encroaches on the implant. In contact osteogenesis, new bone forms first on the implant surface as it becomes colonized by bone cells before bone matrix formation can begin.

As surface characteristics modulates the outcome of cells behavior to the presence of a dental implant and subsequently the osteointegration level, the development of an implant surface that aims to attract osteoblasts that produce a bone extracellular matrix to ensure a high bone-implant contact has been the aim of several research studies over the last years.For this purpose, numerous surface engineering methods have been developed to create featured implant surfaces in order to improve the clinical performance of implants and to guarantee a stable mechanical bone implant interface.[16] Also, persistent efforts have been made in order to enhance the surface properties of dental implants to meet the increasing demands of implant treatments in an aging society and address the associated challenges, such as improving the success rate, expanding the applicability, and shortening the healing time required for sufficient bone-implant integration.[17]

Biocompatibility of Titanium and Its Alloys

Materials compatibility is the most important issue to be considered for a successful dental implantation. Titanium and its alloys are well known as materials that are well tolerated by living tissues and capable of promoting osseointegration.[18]Kokubo treatment, also known as simulated body fluid (SBF), is a chemical method for inducing or determining a level of biocompatibilities property of dental materials that was established in 1991.[19]SBF can be described as a solution with ion concentration similar to human blood plasma, kept under mild conditions of pH and identical physiological temperature.[20]

II. Morphological Surface Modification

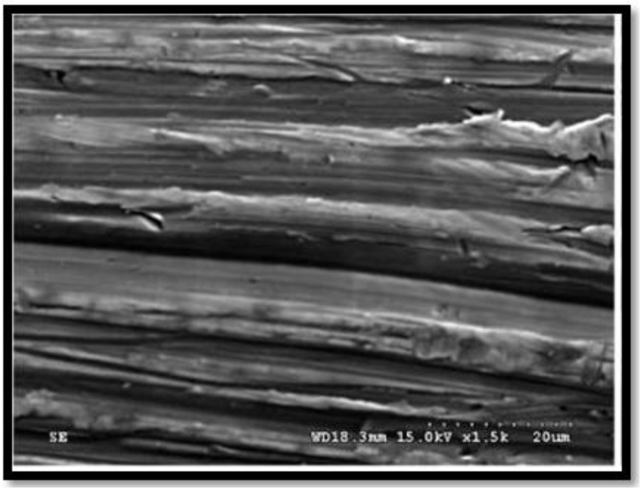
By increasing the surface roughness, an increase in the osseointegration rate and the biomechanical fixation of titaniumnimplants have been observed.[21-22] The implant modifications can be achieved either by additive or subtractivemethods. The additive methods employed the treatment inwhich other materials are added to the surface, either superficialor 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 crystals within TiO2 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 (HA) coating, alumina coating, and biomimetic calcium phosphate (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.[23]

The removal of surface material by mechanical methods involved shaping/removing, grinding, machining, or grit blasting via physical force. A chemical treatment, either by using acids or using alkali solution of titanium alloys in particular, is normally performed not just to alter the surface roughness but also to modify the composition and to induce the wettability or the surface energy of the surface.[24]

As for physical treatment such as plasma spray or thermal spray, it is often carried out on the outer coating surface to improve the aesthetic of the material and its performance.Additionally, ion implantation, laser treatment and sputtering[25-29], alkali/acid etching[30-32], and ion deposition[33] are also utilised.

A. Turned or Machined Dental Implant Surface

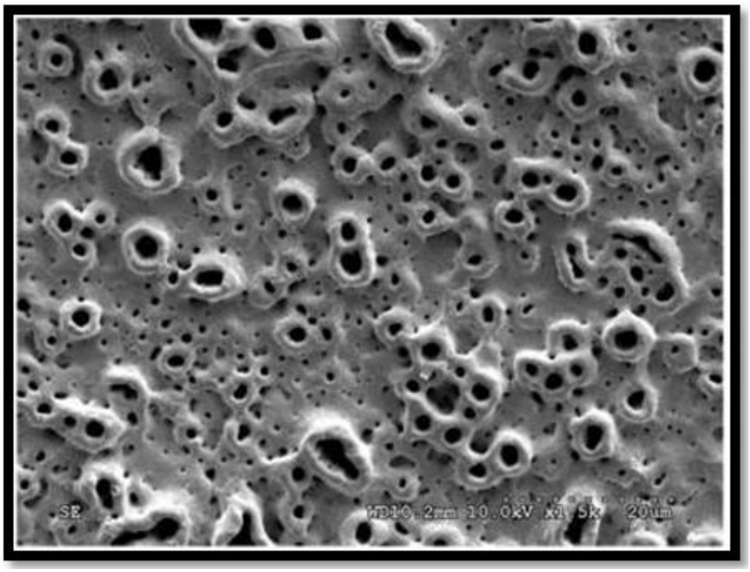
The first generation of dental implants, termed the turned implants, had a relatively smooth surface after being manufactured, are submitted to cleaning, decontamination and sterilization procedures[34]. This surfaces are usually and inadequately called “smooth” since scanning electron microscopy analysis showed that they have grooves, ridges and marks derived from tools used for their manufacturing which provides mechanical resistance through bone interlocking.[35] 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.[36] The success rates of turned implants in challenging situations such as low bone density has 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.



Scanning Electron Micrograph ofTurned or Machined Dental Implant Surface

B. Anodic oxidation

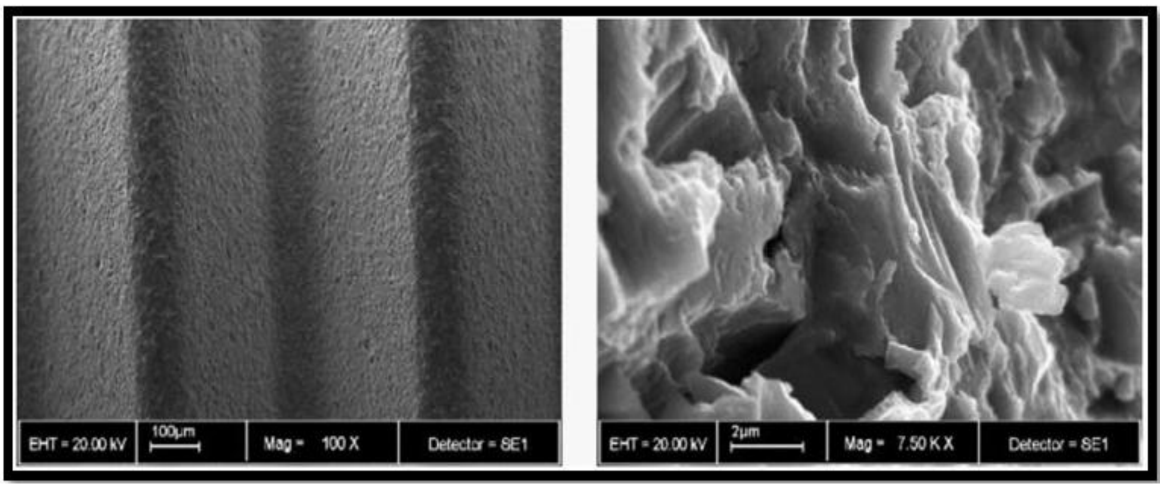
In order to alter the topography and composition of the surface oxide layer of the implants ,micro- or nano-porous surfaces may also be produced by potentiostatic or galvanostaticanodization of titanium in strong acids, such as sulfuric acid, phosphoric acid, nitric acid and hydrogen fluoride at high current density or potential[37]. 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 creates micro-or nano-pores on the titanium surface[38]. This electrochemical process results in an increased thickness and modified crystalline structure of the titanium oxide layer. However, it is a complex procedure and depends on various parameters such as current density, concentration of acids, composition and electrolyte temperature.



Scanning Electron Micrograph ofAnodic Oxidation

C. Grit-blasting

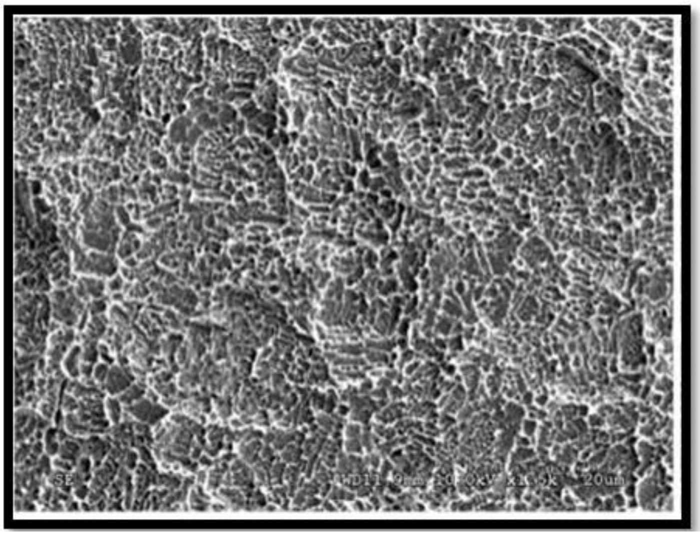
Grit-blasting, consists in the propulsion towards the metallic substrate of hard ceramic particles that are projected through a nozzle at high velocity by means of compressed air and leading to different surface roughness, depending on the size of the ceramic particles. The grit blasting technique usually is performed with particles of silica (sand), alumina, titanium dioxide or resorbablebioceramics such as calcium phosphate. Alumina (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[39]. Moreover, this chemical heterogeneity of the implant surface may decrease the excellent corrosion resistance of titanium in a physiological environment. Titanium oxide (TiO_2) particles with an average size of 25 μm can produce a moderately rough surfaces in the 1–2 μm range on dental implants.



Scanning electron micrographs of a TiO blasted surface

D. Acid-etching

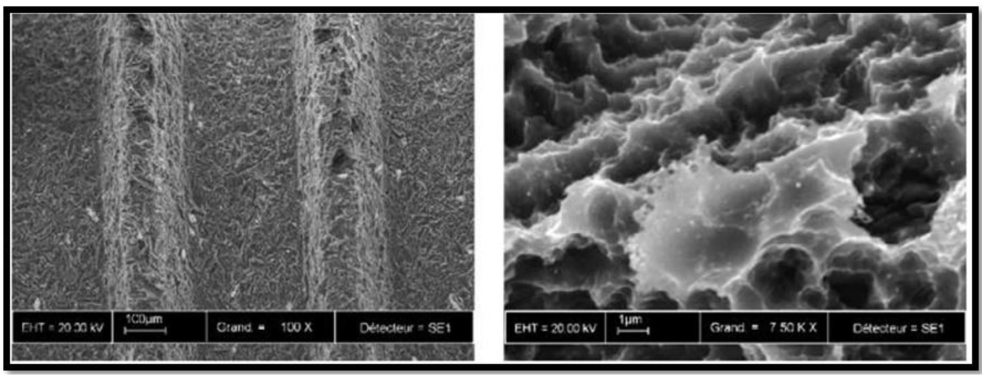
The immersion of a titanium dental implant in strong acids such as hydrochloric acid , sulfuric acid, nitric acid and hydrogen fluoride is another method of surface modification which produces micro pits on titanium surfaces with sizes ranging from 0.5 to 2 µm in diameter[40]. The resulting surface shows an homogenous roughness, increased active surface area and improved adhesion of osteoblastic lineage cells[41]. Dual acid-etching consist in the immersion of titanium implants for several minutes in a mixture of concentrated HCl and H2SO4 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[42]. 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[43]. 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 wich is related to the occurrence of fracture in dental implants.



Scanning electron micrograph of an implant surface processed with dual acid-etching procedure

E. Grit-blasting and Acid Etching

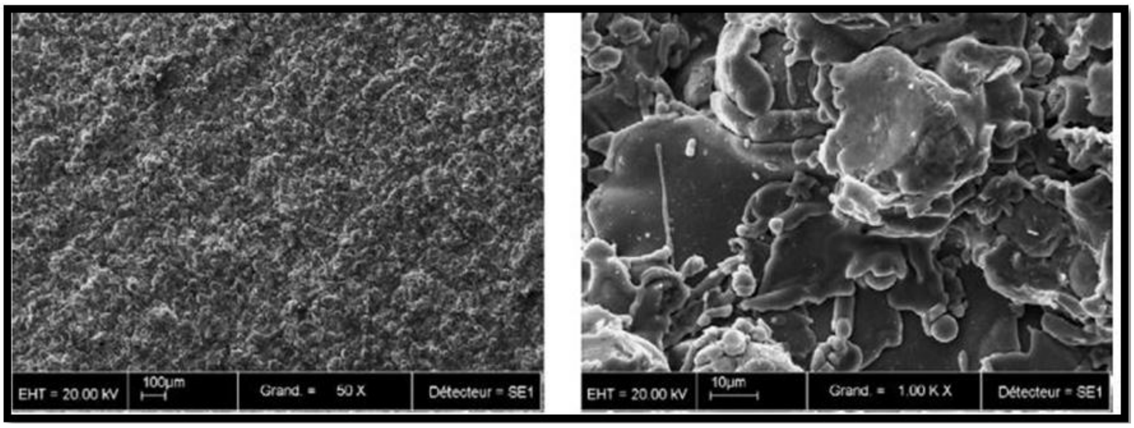
Following grit-blasting , the surface is submitted to acid-etching to further enhance the topographic profile of the surface and remove processing byproducts. The advantages of this method include an increase in the total surface area of the implant, achieved due to the selective removal resulting from 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 removes any particle remainaning, 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[44].



Scanning electron micrographs of an SLA surface on Titanium dental implant

F. Plasma-spraying

Titanium plasma-spraying (TPS) consists in injecting titanium particles into a plasma torch at high temperature. This 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 [45]. The TPS processing may increase the surface area of dental implants up to approximately six 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 six 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[49].



Scanning electron micrographs of a Titanium plasma sprayed surface

G. Calcium Phosphate Coatings

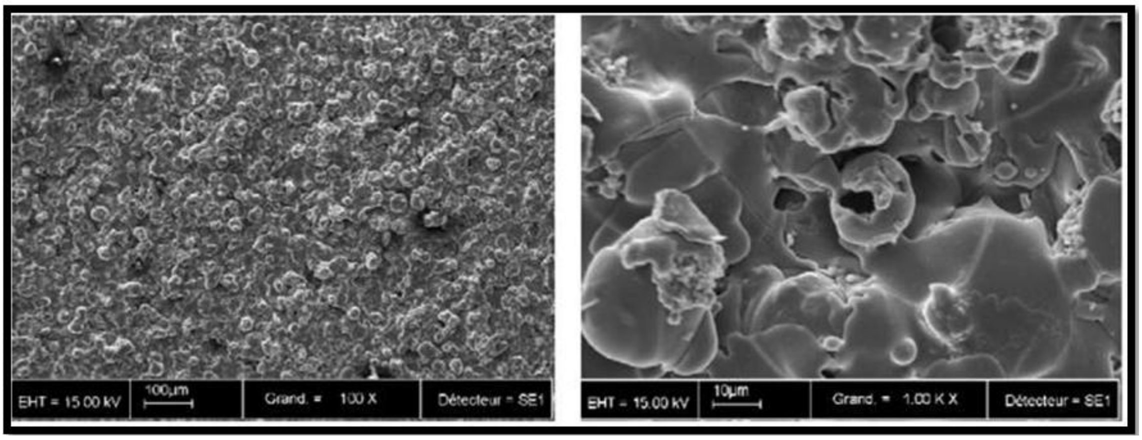
Calcium phosphate (CaP) coatings, mainly composed by hydroxyapatite, has been used as a biocompatible, osteoconductive and resorbable blasting materials[50] The idea behind the clinical use of hydroxyapatite is to use a compound with a similar chemical composition as the mineral phase of the bone in order to avoid connective tissue encapsulation and promote peri-implant bone apposition[51]. 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 calcium phosphate into the peri-implant region increases the saturation of body fluids and precipitates a biological apatite onto the surface of the implant[52].This layer of biological apatite might contain endogenous proteins and serve as a matrix for osteogenic cell attachment and growth and therefore, improve osteointegration.

Plasma Sprayed Hydroxyapatite (PSHA) coatings are the most commonly found among the commercially available calcium phosphate coatings. The HA 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[51]. 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.

Also, 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.



Scanning electron micrographs of a plasma-sprayed hydroxyapatite coating surface

In order to improve PSHA coatings, a number of techniques have been developed with the aim of producing a thin-film nanostructured bioceramic coatings , such as sol-gel deposition, pulsed laser deposition, sputtering coating techniques, electrophoretic deposition and ion-beam-assisted deposition (IBAD)[53]. 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[54].

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 HA coating as it allows for better control of the chemical composition and macrostructure of the coating[55].

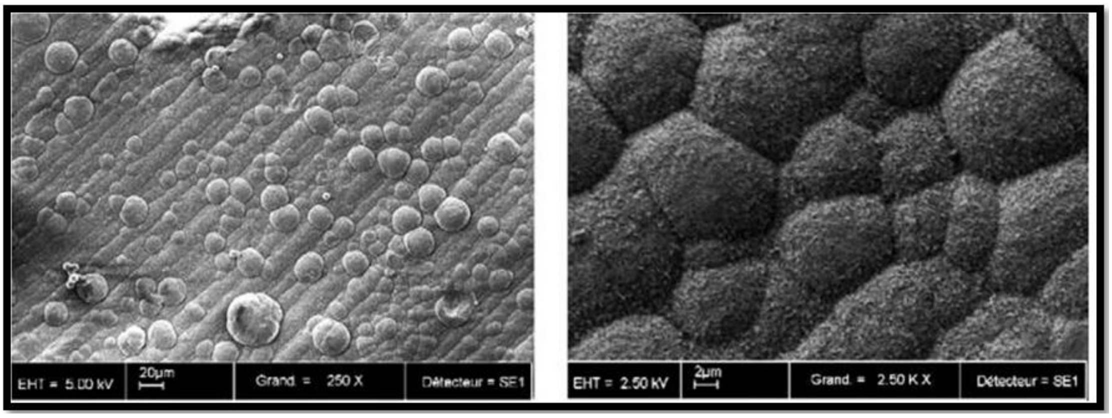
The Pulsed laser deposition results in a titanium surface microstructures with greatly increased hardness, corrosion resistance, and high degree of purity with standard roughness and thicker oxide layer[56].

The Ion-beam assisted deposition technology permits the formation of thin films at atomic and molecular levels, as well as low temperature syntheses utilizing ionic effects[57].

There is an increasing interest in the use of calcium phosphate 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[58]. 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.

H. Biomimetic Calcium Phosphate Coatings

Biomimetic coatings involves the use of microstructures and functional domains of organismal tissue function to deposit calcium phosphate upon medical devices in order to improve their biocompatibility[59]. This bioinspired method consist in the precipitation of calcium phosphate apatite crystals onto the dental implant surface through simulated body fluids under near- physiological or "biomimetic" conditions of temperatutre and Ph



Scanning electron micrographs of a biomimetic calcium phosphate coating

I. Nanotechnology

Nanotechnologies can create surfaces with controlled topography, and chemistry which would help understanding biological interactions and developing novel implant surfaces with predictable tissue-integrative properties.[60]The application of nanotechnology to biomedical surfaces is explained by the ability of cells to interact with nanometric features, which is mainly mediated by integrins, binding to the arginine-glycine-aspartate sequences of peptides. Cell adhesion to the extra-cellular matrix (ECM) leads to clustering of integrins into focal adhesion complexes (FA), and activates intracellular signaling cascades.[61] Nanofeatures are crucial to modulate stem cells behavior.[62] Osteoblasts are able to encode‖ the 3-dimensional characteristics of the surface like lines, pores or dots and modulate their growth according to the suggested structural features. Hence, the surface pattern in particular has been demonstrated to play a key role.

Numerous techniques are used to create nanofeatures on endosseous implants surfaces, which are as follows,

1. Self-assembly of monolayers (SAMs)
2. Chemical Modifications
A. Anodic Oxidation
B. Acid oxidation or Peroxidation
C. Alkali treatment (NaOH)
3. Physical Modifications
D. Compaction of nanoparticles
E. Ion beam deposition
F. Plasma Spray
G. Grit Blasting
4. Nanoparticle deposition
H. Sol-gel (colloidal particle adsorption)
I. Discrete crystalline deposition (DCD)
J. Lithography and contact printing technique
5. Combination of chemical and physical modifications

Thereis still little evidence of the long-term benefits of nanofeatures, as the promising results achieved in vitro and in animals have still to be confirmed in humans. Additionally, there is a lack of data about the release of metal ions in the surrounding tissues and the possible systemic effects. Moreover, a complicating feature of nanoscale manipulation is that there aremany chemical changes on the bulk material surface and it can be very difficult to investigate positive or negative effects induced[63]. However, the increasing interest in nanotechnology is undoubted and more researches are going to be published in the next years. Ongoing developments suggest that dental implant manufacturers will invest increasing resources to give patients the most durable and most biocompatible material to replace their teeth.

III. Conclusion

Several techniques have been widely studied and developed to modify dental implant surfaces to promote rapid osseointegration and faster bone healing. Several in vivo and in vitro studies demonstrated various novel dental implant surfaces mostly consisting in modifications of commercial available ones. The main shortcoming in dental implant surfaces is empirical nature of manufacturing process as it lacks generalized consensus to make one standard for obtaining controlled topographies. In order to overcome this matter, several in vitro and in vivo studies are still required.

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