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Commentary

Implications of Titanium Surface Modifications on Dental Implants

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Abstract

History of using Titanium in medicine goes back to 1950 when a coincidence led a doctor from the US to notice its biocompatibility. However, it was in 1970 when Brånemark introduced Titanium to dentistry as he observed and defined osseointegration. Since then, the use of Titanium as dental implants to replace missing teeth has become very popular among dentists and patients. This increasing demand led to a continuous research work around titanium, specifically its surface modification as there where it will interact with the surrounding environment on both macrostructure and microstructure levels. It is found that different methods and techniques of surface modification can influence the success and survival of titanium dental implants according to the available literature. In this review, the most common current surface modifications will be presented as well as the ongoing research and recent advancement in that field. It is recommended that research work on surface modifications carries on reaching optimal characteristics for ideal dental implants that would promote healing without complications or harm and at no added expenses.

Keywords: *Titanium; Dental Implants*

Introduction

In the 1950s Titanium got its way into Medicine when Leventhal, a surgeon from Philadelphia, tried it as screws on rat femurs and noticed that it become tighter and more difficult to remove from bone, few years later he tried it on humans and results were promising as he conclude that “titanium is a metal worthy of consideration as a prosthesis” [1,2].

The late Brånemark confirmed Leventhal findings and in 1952 while studying the bone marrow circulation of the rabbit fibula using titanium chambers, when it became time to remove the titanium, he observed that the titanium chambers were inseparably incorporated within the bone tissue [3]. In the 1970s, Brånemark brought titanium to Dentistry and became the “father of modern dental implantology”, he defined the process of “Osseointegration”, suggested the clinical techniques for titanium implant insertion, explained how it works, proposed different designs for the fixture and the titanium surface manufacturing manipulation, and he placed dental implants into the first human patient [4].

Thus, dental implant procedures have increased noticeably worldwide, exceeding one million dental implants placed yearly. Their success is related to the early osseointegration between the implant and the bone tissues. Dental implants geometry, design, and surface topography are crucial for the short/long-term of their success [5]. A sequence of events occurs immediately following the implant placement including the initial interaction between blood and implant surface, where proteins and ligands are dynamically adsorbed onto and released from the implant surface, through an inflammatory process, which is followed by initial bone formation around the implant (modeling), and through several remodeling cycles, where bone achieves highest degree of organization and mechanical properties. Different modification methods utilized for implant surface may lead to different and unique surface properties. These different physio/chemical properties can potentially lead to changes in the host-to-implant response [6].

Titanium

Titanium is a transition element in group IV and period 4 in the periodic table and has an atomic number of 22 and an atomic weight of 47.9. In its elemental form it has a high melting point (1668C) and possesses a hexagonal closely packed crystal structure. Titanium alloys of b-stabilizers known as b-alloys offer the unique characteristic of low elastic modulus and superior corrosion resistance. Therefore, it is considered the material of choice for dental implants where titanium and its alloys are the most common [7].

Titanium's Surface

Looking at the implant surface, we can divide it into different dimensions and levels as follow.

Surface Macrostructure: When we look at the implant fixture by the naked eye, we can see its design and geometry, a wide variety of designs has been introduced over the past four decades, but the most dominant these days are the cylindrical threaded ones. As explained before, following an implantation, several phases occur in which stability and load transfer are important. Threads on cylindrical implants improve the implant stability and help the surgeon in placing the implant in the pre-drilled cavity. The improved bone healing around screw-shaped implants has also been observed and confirmed by Albrektsson in 1993 [8]. The introduction of threads on cylindrical implants resulted in beneficial outcomes from proper distribution of stress applied on the implant (evenly distributed load), especially with longer implants, to increased retention when the screw diameter and thread length are increased [9]. In a recent thesis Hansson presented another threading profile with minute threads with a depth of only 0.1 mm (Figure 1 and 2). These authors argue that this type of threads have improved capacities to carry load [10]. These findings are in accordance with recent findings by Wong M., *et al*. [11] that demonstrated improved push-out strength for implant surfaces with many small peaks compared with a surface with high, but few peaks [12].

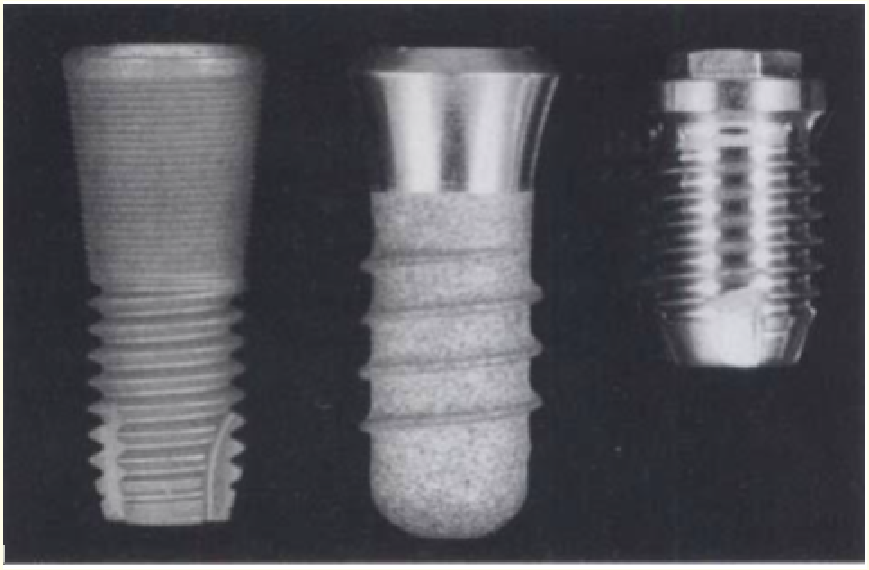

Figure 1: *Surface Modifications of Titanium Dental Implants [12].*

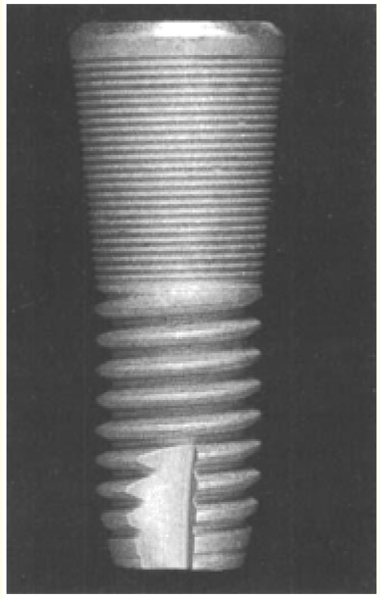

Figure 2: *Combination of microthreaded and conventional-threaded: AstraTechST (Molndal, Sweden) [12].*

Surface Microstructure: Another important factor of the surface configuration and depends on the surface treatment of the implant which varies to influence the stress distribution, retention of the implants in bone and cell responses to the implant surface. In 1990, Gross had tested in vivo responses to pellet-blasted or flame-sprayed cylinders made of titanium and Ti6Al4V alloy and to titanium rods flame-sprayed with hydroxyapatite which were implanted into rabbit femurs and concluded that each implant should have a micro-roughness that allows fixation of trabeculae and consequently a transmission of forces as implants with rough surfaces had improved bone response with bone trabeculae growing in a perpendicular direction to the implant surface and improved retention in bone [13]. On a micrometer scale, the ideal surface roughness depends on several factors, but an optimal surface roughness has been proposed based on experimental studies. Wennerberg tested four different surface structures created by blasting with Al2O3 or TiO2 and machined surface, and she concluded that that implants with a surface roughness of Sa 1 to 1.5 microns seemed to be at an optimal roughness with regard to retention in bone as well as bone to implant contact as measured by histomorphometry [14].

Surface Ultra-structure: These are surface alterations on the nanostructure level where biological responses were observed. Larsson studied a surface treated by anodization where the oxide thickness of titanium changes from electropolished level (amorphous metal surface with a non-crystalline oxide) to thick oxide layers (polycrystalline metal surface with a crystalline oxide) and it seemed to have a slightly improved response in bone, particularly the first weeks after implantation [15].

Surface modification methods and their benefits

Mechanical Methods: Involves physical treatment, shaping, or removal of the materials surface aiming to obtain specific surface topographies and roughness, remove surface contamination and improve adhesion in subsequent bonding steps, examples of these methods are; machining, grinding, polishing, and blasting [7].

Chemical Methods: Include chemical treatment, electrochemical treatment (anodic oxidation), sol-gel, chemical vapor deposition (CVD), and biochemical modification. Different type of reactions occurs within each of these methods.

1. **Chemical treatment:** Based on chemical reactions occurring at the interface between titanium and a solution. The common ones are acid, alkali, H_2O_2, heat, and passivation treatments.

    a. **Acid treatment:** Used to remove oxide and contamination to obtain clean and uniform surface finishes, usually this is used in combination with other treatment methods to improve the property of titanium and its alloys as in Wen., *et al.* when reported that employing ($HCl+H_2SO_4$) and alkaline solution improves bioactivity of Ti alloy.

    b. **Hydrogen peroxide treatment (titania gel coating):** Improves bioactivity of titanium because titania gels can induce the formation of apatite ($Ti+H_2O_2$=Ti peroxy gels).

    c. **Alkali treatment:** In combination with heat treatment it improves the bioactivity by enabling the formation of bone like apatite. Osteoblastic differentiation in bone marrow cells on the alkali-heat-treated titanium and apatite formed titanium were examined by Nishio [16]. revealing that apatite formation played an important role in osteoblastic differentiation. Bone-like apatite formed titanium after alkali- and heat treatment were observed to provide the most favorable conditions for bone marrow cell differentiation [7].

2. **Sol-gel coatings:** A sol is a colloid suspension of solid particles in a liquid and a gel is a substance that contains a continuous solid skeleton enclosing a continuous liquid phase, sol-gel process can be divided into five main steps: (a) hydrolysis and polycondensation, (b) gelation, (c) aging, (d) drying, and finally (e) densification and crystallization.

    a. **TiO_2 coating (Titania):** Results in improved bone-like hydroxyapatite formation and improved blood compatibility.

    b. **Calcium phosphate coatings (Hydroxyapatite):** It improves activity and functionality of cells according to a study by Kim., *et al.* [7], early attempts to use thick calcium phosphate coatings have not yet reached commercial and clinical success in dentistry, but a review of ultrathin coating can improve bone integration without the setbacks of thick coatings [17,18].

    c. **Titania/hydroxyapatite composite coatings:** It is a combination of the hydroxyapatite's bioactivity and the Titania's strong adherence to titanium, so both make it up for each other where the other is deficient at. Therefore, this composite coating will improve bioactivity and adherence.

    d. **Silica coating:** It gave rise to excellent surface properties including high bonding strength to the metal substrate, small amount of leached titanium ions, and high hydrophobicity (81.6' and 105.7' of contact angle of water, respectively). It was found that the bond strength of dental resin cements to titanium can be improved, the release of titanium ions from the substrate can be mitigated, and accumulation of dental plaque on intraoral dental devises can be reduced [7].

3. **Anodic oxidation:** Metal and oxygen ion diffusion leading with electrode reaction leading to the formation of an oxide film on the anode surface. Its main advantage is improved adhesion and bonding, it can also increase the oxide thickness which increases corrosion protection and decreases ion release, coloration, and porous coatings [7].

4. **Chemical vapor deposition (CVD):** A process involving chemical reactions between chemical in the gas phase and the sample surface resulting in the deposition of a non-volatile compound on the substrate. It improves the tribological properties by deposition of polycrystalline diamond films onto titanium substrates since diamond has the highest hardness and heat conductivity of all known materials [7].

5. **Biochemical modification of titanium and titanium alloys:** The objective of modification is to induce specific cell and tissue response by means of surface-immobilized peptides, proteins, or growth factors:

    a. **Salinized-Titania:** Enhance wettability, adhesion, and surface activity.

    b. **Photochemistry:** Used to graft biomolecules onto titanium surface.

    c. **Self-assembled monolayers (SAMs):** Add wettability and electrical charge to the targeted surface.

    d. **Protein resistant and protein immobilization:** Bone morphogenetic protein (BMPs) immobilized on the surface of titanium to increase bioactivity.

    e. **Native oxide on titanium:** It is beneficial to the adhesion of many proteins [7].

Physical Methods: No chemical reaction, modifications are attributed to the thermal, kinetic, and electrical energy.

1. **Thermal spraying:** Materials are thermally melted into liquid droplets and introduced energetically to the surface on which the individual particles stick and condense.

    a. **Plasma spraying:** Can be hydroxyapatite coating where poor bonding between the coating and titanium is one of the main disadvantages or can be calcium silicate coating which has excellent bioactivity and bone conductivity, or finally can be titanium coating where mechanical interlocking is achievable.

    b. **Other thermal spraying:** HOVF and DGUN.

2. **Physical vapor deposition (PVD):** Include evaporation, sputtering, and ion plating. Evaporation is carried out in vacuum.
    a. Evaporation.
    b. Ion plating.
    c. Sputtering.

3. Glow discharge plasma treatment.

4. Ion implantation and deposition.
    a. **Oxygen implantation:** Wear resistance, corrosion resistance, and increased biocompatibility.
    b. **Nitrogen implantation:** Good electrical conductivity and excellent adhesive layer.
    c. **Carbon implantation and deposition:** Improve mechanical properties, corrosion resistant and biocompatible.
    d. **Metal ion implantation:** Enhance surface bioactivity [7].

Wennerberg and Albrektsson classified the commonly used techniques to alter surface topography as subtractive processes where particles are removed from the surface creating pits or pores on it (concave profile) i.e. electropolishing, mechanical polishing, blasting, etching, and oxidization, or as additive processes where materials are added on the metal bulk creating a bumpy surface (convex profile) i.e. HA and other calcium phosphate coatings, titanium plasma sprayed (TPS) surfaces, and ion deposition [19].

Clinical Effects

More implants with rough surfaces were affected by peri-implantitis which means that turned implant surfaces had 20% less risk of being affected by peri-implantitis over a period of three years [18].

Trials and studies found that blasted+etched surfaces (moderately rough) are stronger integrated in bone than machined and TPS surfaces. Oxidized implants show better bone anchorage than machined implants with the advantage to oxidized implants if the loading to be during healing. Disadvantages regarding marginal bone resorption were found in clinical research around TPS surfaces in comparison with turned surfaces. The importance of nanometer structures on implant integration in bone is investigated in few existing studies indicating that it does have an impact on the early bone healing [19]. Even though the implant design and the TPS surface had been removed from the market, it appears that the drawbacks related to the implant design and surface characteristics did not provoke severe bone loss for most implants [20].

Treated Titanium implants form a rutile layer improving corrosion resistance and reducing the friction coefficient of rubbing contact, since rutile is mainly composed of TiO_2 these surfaces improve osteoblast adhesion *in-vitro* and increase the bone-to-implant contact *in-vivo*. Studies showed that treating human primary macrophages with Ti particles releases much higher levels of inflammatory cytokines than rutile, which only stimulates marginally detectable levels of secretion and these results support the higher biocompatibility of Titanium implants modified to create an external rutile layer on their surfaces which can mean better healing initiation. Data suggested that sol-gel treated nano porous Ti implants which has been shown to improve soft-tissue healing *in-vivo* with no increased bacterial adhesion or biofilm formation by 2 commensal species tested in comparison with other surfaces. However, it is still uncertain in the literature what the ideal implant surface should be to reduce bacterial adhesion to achieve an optimal healing [21].

Sand-blasted and acid-etched implants demonstrated high 10-year survival and success rates, with a 98.8% survival rate in a study done in the University of Bern hospital [22], these results can be questionable knowing that the prevalence of patients with periodontitis and heavy smokers was low, and about 70% of these implants were placed by one experienced implant surgeon, but knowing that standard implant placement without bone grafting in this study was higher than in daily practice favors it.

Recent advancements in research

- A study conducted in China published in 2010, authors successfully prepared pure chitosan and chitosan/gelatin coatings on titanium substrates via electrophoretic deposition (EPD), they found that the addition of gelatin increased the shear strength of coatings and improved biological response of osteoblastic cells when tested *in-vitro* (Figure 3) [23].

- Another study in Taiwan has successfully applied plasma-spray technology to an HA spray for titanium surface modification resulting in an almost entirely and uniformly covered dental implants by HA coating indicating high biocompatibility for bone regeneration and insulation against the ion release of titanium implants [24].

- De Maeztu studied ion implantation as a surface treatment for dental implants in human and concluded that a greater degree of bone integration occurred in surfaces underwent CO ion implantation treatment and no adverse reactions were observed in these surfaces which confirm the positive benefits in humans based on previous findings in animals [25].

- A very recent technology called white coating of Ti implants was first studied in early 2014 in Germany, they obtained the white coated Ti topographies by anodic plasma-electrochemical oxidation, it exhibited good *in-vitro* influence on osteoblast cells, high rate of proliferation, and upregulates the expression of osteocalcin and bone sialoprotein, the results open the door toward a new generation of white dental implants [26].

- Not many articles in the literature discuss the problems associated with surface modifications, but a recent study submitted about 6 months ago in Haifa performed a mechanical assessment of grit blasting surface treatments of dental implants and concluded that uncontrolled surface roughening grit-blasting treatments can induce significant surface damage which accelerate fatigue fracture under certain conditions, even if those treatments are beneficial to the osseointegration process [27].

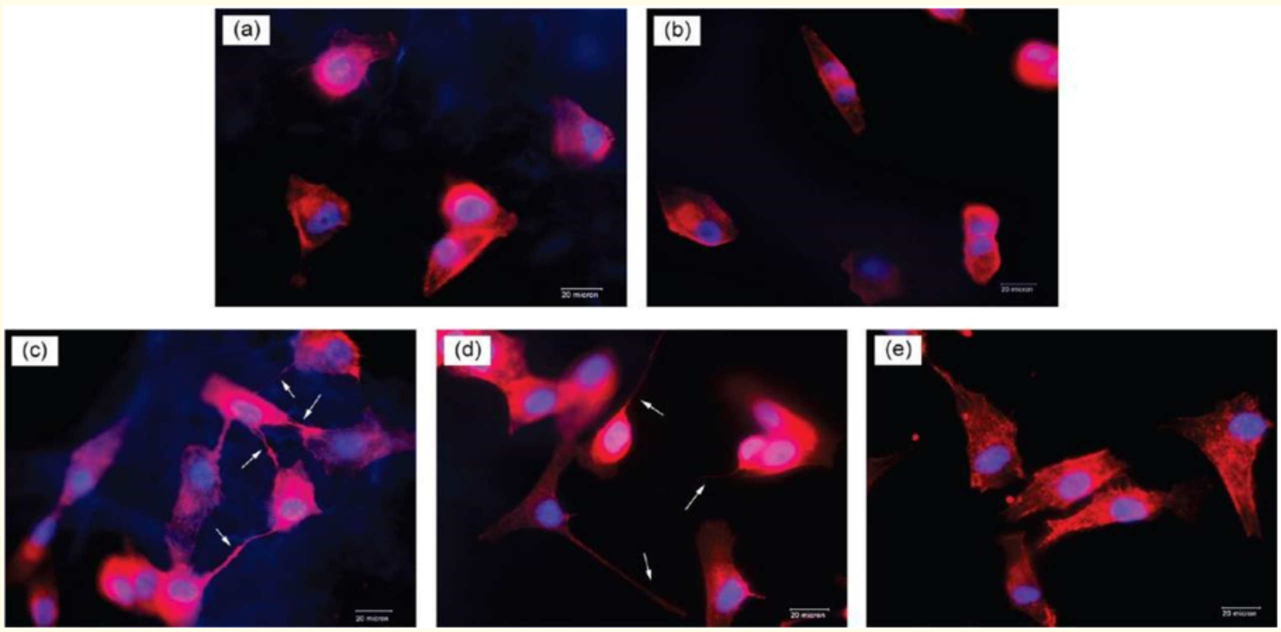

Figure 3: *Fluorescence images of cells skeletons: (a) pure chitosan coating; (b) CS/G30 coating; (c) CS/G50 coating; (d) CS/G70 coating; and (e) titanium. MG63 cells attached to CS/G50 and CS/G70 coatings displayed more bundles (arrow) of actin microfilaments than pure chitosan and CS/G30 coatings [23].*

Conclusion

Finally, the concluding remarks would be that many laboratory projects and researches are still ongoing to make the titanium-to-bone interface more understandable, so manufacturers can someday reach an optimal surface characteristics to help clinicians achieve a successful implant treatment that can survive for decades using titanium implants surfaces treated with the latest technologies that promote ideal healing process without complications at no extra cost, and avoid other surfaces that scientific evidences proved their negative clinical effects, it might sound a dream but recent studies are exhibiting a very promising near future

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