Surface Modifications for Endosseous Dental Implants

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ABSTRACT

Since, the inception of the vast field of implantology in 1969, this method still remains a popular and reliable one for the replacement of missing teeth. Over the years designs by various researchers have been introduced as well as modifications to the surface of the titanium being used. Characteristics of titanium implant surfaces have been modified by additive methods (e.g. titanium plasma spray) to increase the surface area and provide a more complex surface macrotopography. Subtractive methods (e.g. blasting, acid etching) have also been used to increase the surface area and to alter its microtopography or texture.

The field of surface modifications is vast and constantly evolving to keep up with technology, incorporation of biologically active substances, drugs and growth factors is an area of ongoing research. This review article entails the various surface modifications and the latest surface treatments that the world of oral implantology has to offer.

Keywords: Endosseous implants, Surface treatments, Surface texture.

INTRODUCTION

Osseointegration of an implant and events leading to the ultimate success or failure of the device takes place largely at the tissue implant interface. Development of this interface is complex and involves numerous factors.[1] Implant surfaces probably have the greatest potential for enhancement in implant dentistry. Characteristics, such as surface composition, surface topography, surface roughness and surface energy affect the mechanical stability of the implant–tissue interface.[2-4]

Endosseous dental implants are available with various surface characteristics ranging relatively smooth-machined surfaces to more roughened surfaces by coating, blasting by various methods, by acid treatments or by a combination of the treatments.[5] The ultimate goal of modern implantology is fine and fast osseointegration, which is largely dependent on the implant surface itself. This review details the evolution of surface treatments over the years and its use in modern implantology.

Response of the tissues to the implant is largely controlled by the nature and texture of the surface of the implant. Textured surface also allows ingrowth of the tissues.[6,7] Some of these have the ability to enhance and direct the growth of bone and achieve osseointegration when implanted in osseous sites.[8] Altering the surface topography of an implant can greatly improve its stability.[8] Based on the scale of the features, the surface roughness of implants can be divided into macro-, micro- and nano-sized topologies.[9,10] Surface irregularities of an implant can be designed by making porous and/or by coating the implant surface with other suitable materials to increase bone–implant contact since the anatomic surface of bone cannot be controlled.[11] One of the three-dimensional parameters for surface roughness is average surface roughness (S_a) which represents the arithmetic mean of deviations in roughness from the mean plane of analysis. Surfaces with S_a between 1 and 2 µm are included in the moderately rough surfaces.[12] Surfaces with S_a greater than 2 µm are 'rough' surfaces. Surfaces with intermediate roughness (S_a = 1.5 µm) had higher bone to implant indices.[13]

A bioinert surface is one which itself does not play a role in osseointegration. It merely forms a favorable substrate for the osseous deposition to occur, whereas a bioactive surface is one which actively participates in the osseointegrative process due to the reaction between the chemically modified surface coating and the surrounding bone. Successful osseointegration is usually associated with osteogenesis, osteoconduction and osseoinduction. Osteogenesis is the formation and development of bone. Osteogenic cells encourage bone formation in the soft tissues or activate more rapid growth in osseous sites. Osteoconductive surfaces are conducive to bone growth and allow bone apposition from existing bone, but they do not produce bone formation. To encourage bone growth across its surface an osteoconductive surface requires the presence of existing bone or differentiated mesenchymal cells. Substances, such as calcium phosphate and hydroxyapatite (HA) coatings can be classified as such. Osteoinduction is the process of stimulating osteogenesis, osteoinductive surfaces enhance bone regeneration and may even cause bone to grow or extend into an area where it is not normally found. Examples of such surfaces are those coated with collagen-chitosan polymers, which are often used for orthopedic implant purposes.

Surface irregularities can be produced through ablative/subtractive procedures or additive procedures:

Ablative procedures	Additive procedures
• Grit blasting	• Plasma spraying
• Acid etching	• Electrophoretic
• Anodizing	deposition
• Shot/laser peening	• Sputter deposition
	• Sol gel coating
	• Pulsed laser deposition
	• Biomimetic precipitation

Grit Blasting

Titanium surfaces can be grit blasted with hard ceramic/ metallic particles in order to roughen them. The particles are projected through a nozzle at high velocity by means of compressed air, depending on the size of the particles; different surfaces of roughness can be produced on titanium implants.[10] The blasting material should be chemically stable, biocompatible and should not hamper the osseointegration of the titanium implants. Various particles, such as alumina, titanium oxide and calcium phosphate are often used.

Alumina oxide particles having an average size of 300 μ are often used as a blasting material and produce a surface roughness varying with geometry with the granulometry of the blasting media.[14] However, the blasting media is often embedded into the implant surface and residue remains even after ultrasonic cleaning, acid passivation and sterilization. Alumina is insoluble in acid and often hard to remove from the titanium surface; often these residual particles have been released into the surrounding tissues and interfered with the osseointegration of the implant.

Titanium oxide is also used for grit blasting dental implants; they have an average size of 25 μ and produce a moderately rough surface in the 1 to 2 μ range.

Studies[15-18] show that the torque force increased with the surface roughness of the implants. Calcium phosphates, such as HA, beta-tricalcium phosphate and mixtures have been used as blasting media. These materials are in the range of 75 to 85 μ[19] and are resorbable, biocompatible and osteoconductive leading to a clean, pure titanium surface.

Acid Etching

Modifications of the implant surface features an increase in retention between the implant and the bone by enlarging the contact surface, increasing the biomechanical interlocking between implant and bone and by enhancing osteoblast activity with quicker formation of bone at the interface.[20] Acid etching appears to greatly enhance the potential for osseointegration especially in the earliest stages of peri-implant bone healing. Also with this technique there

is no need for any external agent that contaminates the implant surface. Acid treatment produces a clean highly detailed surface texture and lacks entrapped surface material and impurities. This has been reported to have[21] a positive effect on the biologic response in terms of bone apposition, a higher percentage of direct bone to implant contact and strong implant anchorage. Studies[14,22,23] demonstrated optimal surface roughness of particles of 75 μm made surface more resistant to torque and greater bone to metal contact than small (25 μm) or coarse (250 μm) particles. Also precise acid selection and the sequence of processing played the main role in preparation of the rough titanium surface. The surfaces are poorer if they were etched with hydrochloric acid than with sulfuric one. The sequence of sulfuric acid followed by hydrochloric acids showed the best results and since the acid-etched texture is contiguous with the porous coating there is no possibility of debonding or dissolution, thus avoiding concerns with third body wear particles or long-term fixation.

Anodization

Anodization produces modifications in the microstructure and the crystallinity of the titanium oxide layer.[24] Anodized surfaces result in a strong reinforcement of the bone response with higher values for biomechanical and histomor-phometric tests in comparison to machined surfaces. A higher clinical success rate was observed for the anodized titanium implants in comparison with turned titanium surfaces of similar shapes.[21] Micro- or nanoporous surfaces may also be produced by potentiostatic or galvanostatic anodization of titanium in strong acids (H_2SO_4, H_3PO_4, HNO_3, HF) at high current density (200 A/m^2) or potential (100 V). The result of the anodization is to thicken the oxide layer to more than 1,000 nm on titanium. Two mechanisms have been proposed to explain this osseointegration: Mechanical interlocking through bone growth in pores and biochemical bonding. Modifications to the chemical composition of the titanium oxide layer have been tested with the incorporation of magnesium, calcium, sulfur or phosphorus. It has been found that incorporating magnesium into the titanium oxide layer leads to a higher removal torque value compared to other ions.[25]

Shot Peening/Laser Peening

Shot peening[26] is similar to sand blasting, where the surface is bombarded with small spherical particles, each particle on coming in contact with the surface causes small indentations or dimples to form. Laser peening involves the use of high intensity (5-15 GW/cm^2) nanosecond pulses (10-30 ns) of a laser beam striking a protective layer of

paint on the metallic surface. These implants demonstrate a regular honeycomb pattern with small pores.[27]

Additive Methods

Implants have been coated with layers of calcium phosphates mainly composed of HA. Following implantation, the release of calcium phosphate into the peri-implant region increases the saturation of tissue 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. The bone healing process around the implant is therefore enhanced by this biological apatite layer. The biological fixation of titanium implants to bone tissue is faster with a calcium phosphate coating than without.[28] It is well-recognized that calcium phosphate coatings have led to better clinical success rates in the long-term than uncoated titanium implants.[29,30] Classified as a bioactive material, HA has the potential to allow for formation of new bone on its surface, forming a scaffold for bone ingrowth by exchanging ions to create a chemical as well as mechanical bond.[1] HA has been developed as a coating to combine its bioactivity with the strength of a metal substrate.

Several methodologies of HA surface deposition now achieve these fundamental elements to produce surface coating capable of enhanced osseointegration. Such methodologies include plasma spray (PS) and electrophoresis deposited (EPD) and nano-HA.

Plasma-Sprayed HA

The PS process is a type of thermal spray technology that uses a device to melt and deposit a coating material at a high velocity onto a substrate.[31] Adhesion of the HA to titanium is purely mechanical and can be enhanced by a roughened substrate surface.[31] Commercially available PS coatings are reported to have a thickness of greater than 30 μm.[31] The advantages of PS include simplicity, rapid deposition rate, low substrate temperature, low cost and variable coating porosity, phase and structure. Reported problems include poor bond strength between coatings, HA adhesion to its substrate, structural and chemical variation within the coating process and variation between commercial vendors of HA coatings.[32]

Electrophoretic Deposition of HA

EPD is a process in which colloidal particles, such as HA nanoprecipitates which are suspended in a liquid medium migrate under the influence of an electric field and are deposited onto a counter charged electrode. The coating is simply formed by pressure exerted by the potential difference between the electrodes. The operational parameters of EPD can be changed to alter HA surface coating morphology and composition.[33,34]

The reported advantages of EPD encompass its low cost, simple methodology capable of producing coatings of variable thicknesses, high deposition rate, formation of highly crystalline deposits with low residual stresses and ability to uniformly coat irregularly shaped, or porous objects, such as threaded implants due to its high throwing power.[34] EPD can produce HA coatings ranging from <1 to >500 μ thick.

The major disadvantage of EPD is the need for postdeposition heat treatment to densify the coating. Conventional HA feedstocks require temperatures of at least 1,200°C to be densified. Temperatures above 1,050°C affect the oxide layer and mechanical properties of a stainless steel or titanium alloy, as well as decompose HA affecting the interfacial strength between the metal and coating.

One of the major concerns with PS 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. The discrepancy in dissolution between the various phases that make up the coating has led to delamination, particle release and thus the clinical failure of implants.[35]

Recent coating techniques, such as radio frequency sputtering technique,[36] sol gel coating[37,38] and biomimetic precipitation,[28,39] the layer that constituted the calcium phosphate coatings are thin and the bonding between the surface and the underlying titanium is better.

These affect the type of oxide layer formed (anatase or rutile) and affects the apatite deposition and adhesion on the titanium surface. Biomimetic coating technique allows for nucleation and growth of bone-like crystals on a pretreated substrate by immersing it in a supersaturated solution of calcium phosphate under physiological conditions (37°C and pH = 7.4). This method can be modified for the incorporation of drugs or growth factors onto the implant surface thereby making the implants osteoinductive and osteoconductive.

CURRENT TRENDS IN IMPLANT SURFACES

Most of the surfaces currently available have random topography with a wide range of thicknesses, from nanometers to millimeters. Such controlled or standardized surfaces might help to understand the interactions between specific proteins and cells and promote early bone apposition on the implants. Nanotechnologies may produce surfaces with controlled topography and chemistry that would help

in understanding biological interactions and developing novel implant surfaces with predictable tissue-integrative properties.

Many reports have shown that nanometer-controlled surfaces have a great effect on early events, such as the adsorption of proteins, blood clot formation and cell behaviors occurring upon implantation of dental implants. The surface of titanium dental implants may be coated with bone-stimulating agents, such as growth factors in order to enhance the bone healing process locally. Members of the transforming growth factor (TGF-β) super family, and in particular bone morphogenetic proteins (BMPs), TGF-β1, platelet-derived growth factor (PDGF) and insulin-like growth factors (IGF-1 and -2) are some of the most promising candidates for this purpose. Experimental data, in which BMPs have been incorporated into dental implants, have been obtained from a variety of methodologies.[40] Incorporation of bone antiresorptive drugs, such as bisphosphonates, might be very relevant in clinical cases lacking bone support, e.g. resorbed alveolar ridges. The effect of the antiresorptive drug seems to be limited to the vicinity of the implant. Other experimental studies using PS HA-coated dental implants immersed in pamidronate or zoledronate demonstrated a significant increase in bone contact area. The main problem lies in the grafting and sustained release of antiresorptive drugs on the titanium implant surface. Due to the high chemical affinity of bisphosphonates for calcium phosphate surfaces, incorporation of the antiresorptive drug on to dental implants could be achieved by using the biomimetic coating method at room temperatures. However, the ideal dose of antiresorptive drug will have to be determined because the increase in peri-implant bone density is bisphosphonate concentration dependent. The potential risks and benefits of manipulating biomaterial interfaces at the nanoscale will be defined by long-term clinical evaluation of such endosseous devices.

SUMMARY

The final goal of modern implantology is controlled, guided and rapid peri-implant bone healing which leads to fine and fast osseointegration for direct structural and functional connection between living bone and the surface of an implant, allowing early implant loading.[41,42] It is effectively proven that the surface texture of an implant plays a major role in its stability and osseointegration. Clinical judgment of bone quality and quantity, implantation site, as well as biomechanics of the implant and type of final restoration, are important considerations in evaluating the properties and features of an implant system. Constantly evolving frontiers in this vast field are being developed to make quicker and more predictable osseointegration a reality, incorporation of biologically active drugs and bone substitutes create a more favorable bed for osseointegration which further enables faster, safer healing as well as shortened treatment time (Table 1). Clinicians must have knowledge of the cellular and molecular events that lead to osseointegration, because such knowledge is essential to relate clinical findings with basic mechanisms. It is evident that implants should be carefully selected; balancing the research information on their properties with the intended treatment plan (Table 2). Dental implantology is a limitless

Table 1: Modifications of surface treatments

Author	Surface modification	Method of study	Inference
Durual S et al, 2012	SLA titanium coated with titanium oxide by plasma vapor deposition	*In vivo*	Enhanced osseointegration in the first month of healing
Meirelles L et al, 2011	Modified titanium surfaces using plasma immersion ion implantation	*In vivo*	Improved bone formation and higher removal torque values
Alvarez K et al, 2010	One step alkali-heat treatment using a zinc hydroxide complex	*In vitro*	Zinc ion release with improved mechanical interlocking and better implant fixation as compared to conventional NaOH solution
Vidigal et al, 2009	Titanium coated with biomimetic process and plasma-sprayed titanium	*In vitro*	Both coatings induced bone formation, the biomimetic process being a low cost, simple alternative with high potential
Coelho P et al, 2008	Ion beam assisted deposition of bioceramic coating	*In vivo*	300 to 500 nm thickness of ion beam modulated quicker bone healing at early implantation
Bumgarden et al, 2007	Chitosan-coated titanium	*In vivo*	Chitosan-coated implants showed patterns of bone healing and development at the bone implant interface, chitosan coatings can be used for delivery for therapeutic agents, such as growth factors or drugs as compared to uncoated implants

Table 2: Commercially available implant surfaces

Implant	Surface modification
Ankylos Plus, XiVE, Frialit—Dentsply Friadent, GmbH	Sandblasted, large grit blasted, acid-etched
NobelActive—Nobel Biocare, Zurich, Switzerland	Phosphate enriched titanium oxide—TiUnite
GSIII—Osstem, South Korea	Resorbable blast media (RBM)—calcium phosphate hydroxyapatite
NanoTite—Biomet 3i, Palm Beach Gardens, Florida, USA	Calcium phosphate by discrete crystal deposition
Straumann Bone Level—Institut Straumann AG, Switzerland	SLActive—Sandblasted, large grit blasted followed by acid etching
Laserlok Surface—Biohorizon, Birmingham, Alabama	Laser peening
Pitt-Easy—Sybron Implant Solutions GmbH, Germany	Vacuum titanium plasma spray (V-TPS)
Tioblast—AstraTech Dental, Mölndal, Sweden	Grit blasted with titanium oxide
Zimmer Screw Vent	Microtextured hydroxyapatite surface

field with countless possibilities and innumerable benefits and is definitely here to stay.

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