Chapter 6

Treatments to Optimize Dental Implant Surface Topography and Enhance Cell Bioactivity

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Abstract

Osseointegration is a biological process in which histological, surgical, infectious factors, biomechanical load, and the choice of biomaterials all play important roles. In the case of dental implants, the success of this process is also influenced by the design, composition, and properties of the implant surface, which may stimulate cell bioactivity and promote osteoblast adhesion. Currently, the raw materials most frequently used in the manufacture of dental implants are titanium, its alloys, and certain ceramic materials such as zirconia. Multiple macroscopic designs incorporating various diameters, lengths, shapes, and types of screw offer different options for specific clinical situations. The characteristics of implant surfaces have aroused great interest, due to their importance in osseointegration. The different methods used to modify surface properties are classified as additive (i.e., impregnation and coating) or subtractive (i.e., physical, mechanical and chemical methods). The surface characteristics of dental implants also have a significant influence on peri-implant microbiota.

Keywords: Dental implant, Titanium, Osseointegration, Surface roughness, Coating, Peri-implantitis

1. Introduction

Over many years, dental implants have been developed and modified in order to achieve an optimal interaction between the body and the implanted material and thus to improve osseointegration and reduce the complications due to colonization of bacterial plaque [1].

Proper integration of the surface of a dental implant with the surrounding bone is essential to ensure the longevity and function of the prosthesis supported by the implant [2]. The cell adhesion between the bone interface and the implant surface is considered the most biologically important stage in the process. This structural and functional integration is influenced by the activity of adjacent cells and by the properties of the implant surface itself.

Some implant surfaces may influence the differentiation and proliferation of osteoblasts and may affect the regulation of the transcription factors responsible for the expression of the genes associated with the formation of the bone matrix. Their use may even shorten the implant integration period [3].

The treatment of a surface can be classified according to mechanical, chemical, and physical processes. In dental implants, the modifications of the outer surface are designed to modify the topography and surface energy. This improves wettability and increases cell growth and proliferation, which eventually accelerates the process of osseointegration [4–7].

The biocompatibility and roughness of the materials are the key features in the interaction between the tissue and osseointegration [8]. In addition, the surface of dental implants can be significantly increased using suitable modification procedures such as additive or subtractive techniques [9, 10].

2. Biomaterials for dental implants

Currently, the main materials used in the composition of dental implants are commercially pure titanium (cp Ti), Ti alloys, and ceramic compounds.

2.1. Alloys

Titanium (Ti) is a silver-gray, biologically inert transition metal with a high corrosion resistance due to the spontaneous formation of a surface oxide film (3–10 nm thick) which insulates it from the environment [11, 12]. Thanks to its composition and thickness, this oxide layer makes Ti biocompatible. Ti has four grades of purity which are related to the corrosion resistance, ductility, and strength. Grade 1 Ti is the purest and most ductile and has the highest corrosion resistance, but it is also the weakest. Grade 4 Ti is the strongest and has moderate plasticity and is therefore the grade most frequently used in dental implants [13].

Titanium alloys. Manufacturers of dental implants use a specifically designed alloy which has the following composition: 6% aluminum, 4% vanadium, up to 0.25% iron, up to 0.2% oxygen, and 90% Ti [14]. This alloy has a greater corrosion resistance, high resistance to fatigue, and low elastic modulus [11]. Due to the strict mechanical demands on dental implants during chewing, especially in the posterior areas, Ti alloys are preferred to cp Ti [2].

2.2. Ceramic compounds

Zirconia is a highly biocompatible ceramic compound with osseointegration capacity [15, 16]. It possesses ideal physical properties as a biomaterial, with good values of resistance to flexion, hardness, and corrosion resistance. Some authors have reported that zirconia has similar biocompatibility and osseointegration values to Ti [17]. However, other comparisons of the two biomaterials have reported lower osseointegration values for zirconia implants and have attributed these differences to the treatment of the surfaces rather than to the material itself [18].

Zirconia implants, as a substitute for metals, are indicated in the restoration of anterior teeth with aesthetic aims. However, more prospective studies of their survival and long-term stability are required; indeed, some authors still recommend caution with regard to considering zirconia implants [19].

Hydroxyapatite (HA) is a bioceramic used as a surface coating on Ti implants, incorporating calcium phosphates to facilitate prompt osseointegration. HA has excellent biocompatibility, osseoconductive capacity, and satisfactory mechanical properties which make it a good surface biomaterial [20].

Implants with HA coating have demonstrated a faster reduction in early mobility and other potential advantages such as its short-term osseoconductive capacity. However, the rate of long-term survival of these implants is still controversial [21–25].

3. Macro-design of dental implants

The macro-design of dental implants determines their stability and their capacity to withstand the functional loads. The length, diameter, shape, and design of the screw are influential factors in the bone–implant interface. In the long term, these features may even determine the implant's survival.

3.1. Implant length

Implant length is the distance from the prosthetic platform to the apex of the implant. Some authors have reported a lower survival rate for short implants, especially those <7 mm long [26, 27]. Eckert et al. [28], however, noted that the relation between implant length and survival was limited and was only noticeable when implants were <13 mm in length.

The type of bone and the cortical bone anchoring are probably more important factors than the implant length. Nonetheless, the indications of implants with extra short lengths (5–6 mm) should be carefully studied and considered, especially in areas with poor bone quality. Manufacturers are making great efforts to improve these implant surfaces so as to increase the area in contact with the bone and thus improve their prognosis [29, 30].

3.2. Implant diameter

The implant diameter is the distance from the outermost point of the screw to the opposite side. It measures the external dimension of the implant screw and should not be confused with the size of the implant platform.

Implant diameters usually range from 3 to 7 mm to make them compatible with the most sizes of alveolar processes. The choice of diameter depends on both surgical and prosthetic factors. In order to achieve maximum primary stability, the implant should be lodged between the vestibular-lingual/palatal cortical bones. From a biomechanical point of view, wider implants are able to join a larger amount of bone to the implant surface and obtain a higher bicortical anchorage, thus achieving a better distribution of stress in the surrounding bone. Another advantage of large diameter implants is that they can be inserted immediately in failure sites [31–33]. Some authors have found that increasing implant diameter by 1 mm increases the surface of bone–implant contact by 35% [34]. However, another parameter to consider is the crestal bone around the implant. According to Misch [35], this bone has a strong influence on the occlusal load; this author hypothesizes that it may be even more important than the length and diameter of the implant itself.

The primary stability of dental implants at the time of surgery has been considered an important factor for integration [36]. Langer et al. recommended large diameter implants to improve primary stability in low-density bones. The authors argue that increasing the diameter increases the bone–implant contact, thereby reducing initial implant mobility [37].

Small diameter implants have been introduced for narrow residual alveolar ridges and for edentulous spaces with small interdental distances. These implants do not include mini-implants, which are used to hold temporary dentures and have diameters <2.7 mm [38]. The main indications for narrow implants are the lower incisors, upper lateral incisors, and the restoration of teeth with residual spaces smaller than 5 mm without any possibility of space recovery or bone regeneration [39]. The main limitation of these implants is their reduced resistance to occlusal loads [40].

3.3. Implant shape

Shape has been one of the most thoroughly studied aspects of implant design. The most current implant systems are solid cylinders with thread; hollow implants are rare today. As for the design of the thread, attempts have been made to increase their self-threading capacity and to reduce heat generation during implantation. These design variations are most often applied in the crestal and apical areas. Some designs have attempted to imitate the natural root with a stepped cylindrical shape in the apical and crestal third of the implant. Some authors note that stepped cylindrical implants achieve better stress distribution and crestal bone load than conical and cylindrical implants [41].

Kan et al. [42] reported that threaded implants provide the best immediate retention. Other studies show that the use of a serrated thread can increase primary stability and that thread geometry plays an important role in the biomechanical properties of the implants [43, 44].

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4. Dental implant surface treatments

Currently, the most manufacturers of dental implants are introducing changes in implant surfaces in order to improve the success and quality of osseointegration.

Some studies have noted that with greater surface roughness, the rate of osseointegration, and the biomechanical fixation of Ti implants both increase [45, 46]. The methods used to modify the surface properties can be divided into additive and subtractive. Before certain surface treatments, pretreatment such as grit blasting or polishing may sometimes be indicated to guarantee the absence of contaminations, scratches, and irregularities [47, 48].

4.1. Additive methods

Additive methods supply extra materials to the implant surface, either via coating or via impregnation. Coating involves the addition of a material of variable thickness to the surface of the core material. The techniques used are Ti plasma spraying (TPS), plasma-sprayed HA coating, alumina coating, and biomimetic calcium phosphate (CaP). For its part, impregnation requires the full integration of the chemical material or agent into the Ti core. This is the case of CaP crystals within the TiO_2 oxide layer or the incorporation of fluoride ions to the surface [8].

Plasma Spray Coating: The coating process includes the spraying of thermally melted materials on the implant substrates [8]. This technique usually involves a fine layer of deposits such as HA and Ti. The combination of HA coating on Ti alloy substrates offers attractive mechanical properties and good biocompatibility [49]. Plasma spray significantly increases the surface area of the implant by increasing its roughness [50]. Thus, many studies have shown that plasma spray is a good additive method for improving the biomechanical behavior [47, 51–55]. Some studies have even described a possible optimization of scar formation and cell proliferation thanks to HA coating [56, 57].

4.2. Subtractive methods

Subtractive techniques are procedures that remove a layer of core material or deform the surface in order to increase its roughness [58]. These methods can be divided into mechanical, chemical, and physical. Removal of surface material using mechanical methods includes shaping/removing, grinding, machining, or grit blasting using physical force. Chemical treatment of Ti alloys using either alkaline or acid solutions is carried out not only to increase the roughness but also to modify the composition and improve the wettability and surface energy [59]. Complementary physical treatment of the coating surface, such as thermal spray and plasma spray, improves the aesthetic appearance of the materials and their performance [8].

Grit blasting is a mechanical subtractive procedure which increases surface roughness by the pressurized projection of particles onto the surface of the implant. The main materials used are sand, HA, alumina, or TiO_2 particles. After grit blasting, acid etching is applied to remove the residual particles. Grit blasting is one of the most commonly used surface treatments for increasing the surface roughness of dental implants. However, in itself, it does not accelerate the osseointegration capacity [8, 60] (**Figure 1A**).

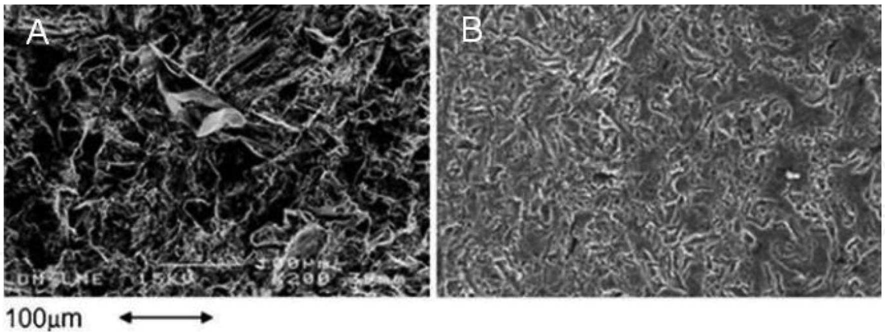

Figure 1. Environmental scanning electron microscope micrograph (ESEM) of the surface of dental implants: (A) shot-blasted; (B) acid etched [66].

Aparicio et al. [61] observed that the increase in the surface roughness of the material induced by blasting in cp Ti was not the only cause of the differences in the electrochemical behavior and corrosion resistance; they also mentioned the compressive residual surface stresses induced by shotblasting.

Commercially, pure Ti is a bioinert material which lacks the ability to establish chemical bonds with surrounding bone. Kokubo et al. [62] demonstrated that the treatment of this Ti with heat and alkali procedures rendered it bioactive. Aparicio et al. [63] observed that the surface of the implant achieved by grit blasting and thermo-chemical treatment improved adhesion and differentiation of human osteoblasts. Gil et al. [64] also observed positive results for this bioactive Ti, although improvements are necessary in order to prevent bacterial colonization. It is important to bear in mind that bacteria have a greater capacity to colonize rough surfaces [8] (**Figure 2**).

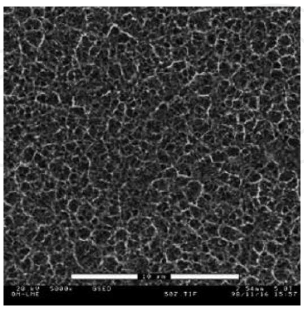

Figure 2. ESEM micrograph of the sodium titanate surface of the implants treated by shotblasting and thermochemical treatment (two-step treatment) [66].

Some researchers have found that the apatite layers formed on grit-blasted surfaces have a higher adhesion strength to the substrate than plasma-sprayed apatite coatings. They note the potential clinical application of this type of surface treatment in dental implants [65].

The evolution of bioactive surfaces into osseoconductive biomimetic surfaces (Contact Ti) was described by Gil et al. In this process, a CaP layer is obtained on the implant surface by thermochemical treatments. This achieves a structure equal to the CaP formed by the mineral content of the bone (HA). This apatite should not be confused with an additive coating; in this case, there is an extremely strong chemical bond and so it is not dislodged by mechanical action. These bioactive implant surfaces significantly reduce the time of osseointegration. The most important mechanisms involved are the protein adsorption capacity, wettability, and an optimized zeta potential which reduces the electrostatic dispersion between particles. Finally, this procedure also aims to increase the kinetics of adhesion, proliferation, and differentiation of osteoblast cells compared to other current surface treatments in order to facilitate bone formation around the implants [66–68] (**Figure 3**).

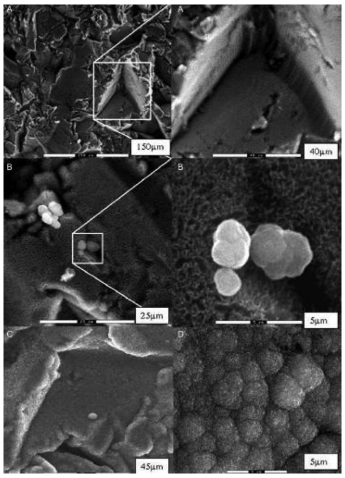

Figure 3. ESEM images showing: (A) 2S bioactive surface; (B) *in vitro* nucleation of apatite on 2S bioactive surface; (C) *in vitro* formed apatite layer on 2S bioactive surface; (D) 2S bioactive surface at higher magnification [67].

Anodic oxidation is an electrolytic process used to strengthen and increase the thickness of the natural oxide layer. This passivation technique manages to turn a smooth Ti surface into a tubular nanostructure with diameters below 100 nm [69]. Some authors suggest that by modifying the parameters of voltage, current density, and chemistry of electrolytes, it is possible to control the physical and chemical properties of the implant surfaces, the spacing, and the diameter of nanotubes [70]. Anodization forms pillar-like nanostructures with tunable size on the surface of Ti and deposits long nanotube arrays (10 microns), thus improving the cell bioactivity [71].

Acid treatment is a chemical subtractive method that cleans the surface of the metal and modifies its roughness. Hydrofluoric acid (HF), nitric acid (HNO_3), and sulfuric acid (H_2SO_4) are commonly used, either alone or in combination [8]. This technique obtains a homogeneous surface roughness for different sizes and shapes. The acid-etched surfaces facilitate the process of osseointegration by increasing the capacity of cell adhesion and bone formation [72–74]. Furthermore, the surface roughness of Ti also determines the stability of the bone formation and resorption at the interface with the implant [75]. The dual acid etching treats the surface by chemical means or by acids applied sequentially or in combination [76, 77]. This technique achieves a surface with micro-roughness, which some authors associate with higher values of reverse removal torque than machined surface implants [78] (**Figure 1**B).

Alkali treatment is a procedure in which the Ti implant is immersed in either potassium or sodium hydroxide followed by heat treatment (800°C for 20 min) and subsequent rinsing with distilled water. This technique achieves a nanostructured and bioactive sodium titanate layer on the surface of the dental implant, which provides favorable conditions for bone marrow cell differentiation [69]. The thermal oxidation works by changing the crystal structure of the nanometric oxide layer and thus increases the bioactivity of a biocompatible metal [79].

Sandblast, large grit, and acid etching (SLA) applies a strong acid on the blasted surface for the purposes of abrasion. The procedure starts with large particle blasting, which obtains a rough, irregular surface. Then, the acid etching produces surface uniformity and obtains a macro-roughness and micro-pits which are able to improve osseointegration. Kim et al. [80] observed that human osteoblasts grow well on the SLA surface which provides space for cell adhesion and proliferation.

4.3. Other techniques

Other procedures such as ion implantation, laser treatment, sputtering, and the combination of some of the techniques already mentioned have also been studied in order to improve the surface properties of dental implants [81–84].

Ion implantation causes atomic rearrangement. It permits the injection of any element on a nearby surface with a beam of high-energy ions (10 KeV) which impacts on the surface of the metal in a vacuum chamber. On colliding with the ions of the substrate material, the incident ions lose energy and settle on the surface of the nearby metal. This technique is considered an ultra clean process because the concentration and depth of the impurities are easy to control, allowing the creation of a layer of high purity. Furthermore, the adhesion between the implanted surface and the substrate is excellent; the process does not alter the properties of the core and is highly reproducible and controllable [85]. However, some authors warn that the possible modification of the nanoscale features and the creation of stress on the Ti surface should be taken into consideration [86, 87].

Ultraviolet (UV) photo-functionalization is one of the recent advances in the chemical modification of implant surfaces which does not alter the bioactive properties.

Laser technology is an extremely clean, fast, and accurate method which allows nanostructural micromachining at the implant surface [88]. Laser peening involves striking the metal with high-intensity pulses of a laser light beam which produces a deep, regular honeycomb pattern with small pores [2].

The slow rate sputter deposition method achieves a thin layer of Ti oxide (300 pm–6.3 nm). This technique increases the oxygen components without altering the surface topography. These biological activities are correlated with the thickness of the TiO_2 coating and the oxygen

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saturation of the surface. This means that the biological response of Ti can be improved even with picometer super thin coatings [69].

5. Peri-implantitis related to dental implant surfaces

Peri-implantitis is an infectious disease of an already integrated dental implant that causes inflammation of the surrounding hard and soft tissue, leading to the loss of supporting bone (**Figure 4** and **5**). The sequence of microbial colonization on dental implants and biofilm formation is similar to that of teeth. The bacteria that colonize dental implants include the same species as those present in healthy gums and in locations with gingivitis [89–91]. Several *in vivo* studies show that streptococci and *Actinomyces* species predominate in the initial colonization; their presence prepares the environment for colonization by other species such as *Porphyromonas*, *Prevotella*, *Capnocytophaga*, and *Fusobacterium* which cause the peri-implantitis [91] (**Table 1**).

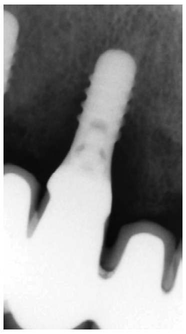

Figure 4. Intraoral radiograph taken 8 years after implant placement—sandblasted, large-grit and acid etched (SLA) surface treatment type. Note the bone crater-like defect around the implant revealing a severe peri-implantitis (*Clinical records*, *Dr. Jaume Miranda-Rius*).

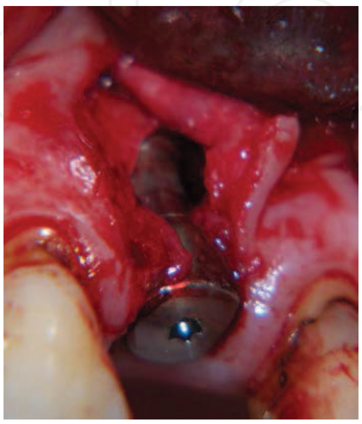

Figure 5. Peri-implantitis clinical image. Surgical debridement of the granulation tissue around the implant (*Clinical records*, *Dr. Jaume Miranda-Rius*).

Streptococcus sanguis	*Capnocytophaga* spp.
Streptococcus mitis	*Campylobacter rectus*
Aggregatibacter actonimycemetcomitans	*Spirochetes*
Porphyromonas gingivalis	*Veillonella parvula*
Prevotella intermedia	*Staphylococcus aureus*
Tannerella forsythia	*Fusobacterium* spp.
Treponema denticola	*Peptostreptococcus prevoti*

Table 1. List of bacterial species associated to dental implant biofilm.

The surface characteristics of dental implants—roughness, wettability, surface free energy, and composition—play a crucial role in bacterial adhesion and colonization. The highest adhesion capacity is observed on rough Ti surfaces. Some authors have observed that mean roughness values below 0.088 microns significantly inhibit plaque adhesion and maturation [92]. Furthermore, decreasing the wettability of dental implants favors bacterial colonization. Some authors suggest that autoclave-sterilized Ti presents a higher rate of bacterial colonization, given the loss of surface wettability (**Figure 5**).

Surface free energy is the sum of the forces of cohesion and adhesion that determine whether or not there is impregnation (the dispersion of the liquid over a surface). Decreasing surface free energy inhibits bacterial adhesion and biofilm formation on the surface of dental implants and abutments [93]. Thus, bacterial adherence is correlated with the presence of surface components with nonpolar or hydrophobic characteristics [93–95]. Finally, the type of metal and its composition also has an effect on bacterial adhesion and biofilm formation on its surface. Pure metals, especially Ti, nickel, iron, and vanadium, have some bacteriostatic capacity [96].

Some authors have concluded that ZnO and TiO_2 reduce the adhesion of staphylococcal bacteria and increase the adhesion of osteoblasts [97]. The addition of silver compounds to increase antimicrobial action has also been studied [98]. Other authors have analyzed the behavior of Ti surfaces modified with vancomycin attached via covalent bonds and have reported a stable surface with a greater inhibition of bacterial adhesion than with Ti alone [99].

6. Conclusion

In this chapter, we have highlighted the important role of the macro- and micro-design of implants and their composition in the process of osseointegration. We have also stressed the significant influence of the surface characteristics of implants on the peri-implant microbiota. All in all, peri-implantitis is an important area for future research. It is extremely difficult to control the progress of an infection once it is established around an implant. The rough surfaces facilitate osseointegration, but also favor the adhesion of oral biofilm. Because of the multi-factorial nature of infectious peri-implant complications, studies should also take into account the influence of the permucosal seal. This biological seal aims to integration the neck of the implant or the abutment with the gingival tissue and thus prevent peri-implant infections. Currently, the challenge in the treatment of implant surfaces is to demonstrate the potential of certain coatings for releasing local antimicrobial agents. Given the clear increase in inflammatory peri-implant diseases, we believe that future research should aim to devise new strategies for obtaining antibacterial biomaterials that can help in the prevention or treatment of peri-implantitis.

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