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Surface Modifications of Zirconia Dental Implant for Improving Osseointegration: A Literature Review

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ABSTRACT

The aim of the current review is focused on compiling a comprehensive overview of the zirconia surface modification for implant interface osseointegration. Background: During the past few decades, the importance of osseointegration for patients has significantly increased, and this importance has been reflected in a sharp growth in the number of relevant items and treatments in that field of implant dentistry, as well as a parallel rise in publications on the subject. The search has been conducted through various databases including Cochrane, Web of Science databases, and Google Scholar, and Ovid Medline, on the given topic. The preferred method of zirconia surface treatment and its effect on osseointegration are briefly reviewed in this article in order to provide a concise summary of the current scientific and clinical viewpoints. Zirconia surface treatment is controversial topic in terms of surface treatment. Surface bio-inertness of zirconia implants result in limited osseointegration compared to titanium implants.

1.Introduction

Due to their outstanding mechanical behavior, corrosion resistance, and biocompatibility, commercially pure titanium and its alloy have been the standard materials for the construction of dental implants (Sivaram et al., 2018). However, an unsightly metallic tinge in the anterior region and a possible hypersensitive reaction have increased the need for novel biomaterials with required biocompatibility and aesthetic standards (Han et al, 2017). Zirconia ceramic has become an interesting choice for dental implant materials over the past three decades because of its acceptable esthetic properties, chemical stability, and low ion release (Han et al, 2017; Cionca et al, 2017). Zirconia, on the other hand, exhibits chemical inertness and stability, with no local or systemic hypersensitivity after implantation, whereas a titanium implant may cause specific immunological reactions (zcan and Hämmerle, 2012). In the meantime, earlier research has demonstrated that zirconia implants exhibit a comparable bone-to-implant contact (BIC) to titanium implants (Bosshardt et al, 2017; Hafezeqoran and Koodaryan, 2017). Zirconia has less bacterial growth than titanium, and titanium raises the chance of peri-implant soft tissue inflammation more than zirconia does.

Zirconia implants are considered as a 'Biologically inert' subject, no effective chemical bonds could be detected between implants and adjacent bone tissues(Siddiqi et al, 2018; Li, 1997). The main problem is how to make zirconia surfaces more bioactive. Surface properties are crucial for osseointegration and the long-term clinical effectiveness of implants (Liu et al, 2010). A greater contact area between the surface of the implant and the bone would eventually result from these properties, which influence protein adsorption and cell activity (Liu et al, 2010; Barfeie et al, 2015). Surface modification is therefore required to improve osseointegration (Pellegrini et al, 2018; Annunziata and Guida, 2015).

Surface modification techniques generally attempt to change surface characteristics, such as (1) surface topography; (2) surface chemistry;(3) surface biochemistry. These three strategies are commonly interrelated (Stefanic and Kosmač, 2014). However, unlike titanium, surface modification of zirconia has been technically challenging and related researches are not sufficient about the survival rate and biocompatibility of zirconia implant , there is also the review of surface modification methods and how they affect osseointegration. As a result, this research provides an overview of different surface modification approaches and how they affect osseointegration. Also, a few new approaches are briefly introduced.

1.1 Modification of surface topography

Surface topography is the degree of roughness, which is classified into three categories based on the scale of the features: macro-, micro-, and nano-sizes, as well as the orientation of surface irregularities (Wei et al, 2014). It has an impact on the biomechanical stability of the implants as well as the adhesion, proliferation, and differentiation of cells around the implants (Stefanic and Kosma, 2014; Tomisa et al., 2011). Compared to a smooth implant surface, a zirconia implant surface that has been roughened promotes greater osseointegration (Liu et al, 2010; Bergemann et al, 2015). Microscopically, surface topography plays a vital role in protein adsorption and the expression of bone-related growth factors, which eventually impact on the formation of bone and extracellular matrix apposition by inducing specific cytokines such as fibronectin, integrin, TGF-β (Feller et al, 2014; Lukaszewska et al, 2018). Many methods, including traditional sandblasting, acid etching, sandblasting-acid etching, lasers, and selective infiltration etching, have been used to alter surface topography (Stefanic and Kosma, 2014).

Table 1: Modification of surface topography

Method	Characteristic	References
Sandblasting	Improve roughness;Low cost Particle contamination ; Cause microcracks	(Yamada et al, 2013; Zhang et al, 2017)
Acid-etching	Eliminate the impurities Change chemical components	(Gomez et al, 2007; Jang et al, 2018)
Sandblasting-acid etching	Enhance the roughness Eliminate impurities	(Scarano et al, 2017; Ito et al, 2013)
Selective Infiltration	Nanometer porous;Selective	(Aboushelib et al, 2007; Nassif and Rifai, 2018)
Etching (SIE)		
Fiber laser	Stable and high-energy beam Short wavelength without spatial fluctuations	(Delgado et al, 2015; Di et al, 2016)
CO_2 laser	Low frequency and small photon energy Causes surface oxidation and brittle rim	(Stübinger et al, 2008; Siqueira et al, 2015)
YAG laser	Shorter wavelength Focused to a smaller spot size	(Di Matteo et al, 2016; Kakura et al, 2014)
Femtosecond laser	Increase surface roughness Reduce the presence of residual elements	(Stübinger et al, 2008; Sugioka et al, 2014; Oyane et al, 2016)

1.1.1 Sandblasting

To make the zirconia implant surface rougher, aluminum or silicon carbide are blasted onto it. Sandblasting, often referred to as airborne particle abrasion, can increase surface area and energy, which in turn improves protein adhesion and cell behavior on the peri-implant (Yamada et al., 2013). Due to their affordability, hardness, and needle-like shape, Al2O3 and zirconia granules with a diameter of 25–250 um are the primary materials utilized for sandblasting.

Bächle M, et al. (2007) found that airborne particle abrasion significantly increases the surface roughness of zirconia implants compared to machined ones, and hence the possibility for cell growth. Furthermore, when compared to machined titanium surfaces, sandblasting considerably promotes peri-implant osteogenesis (Bächle et al, 2007). Nothdurft et al. examined cell responses on machined, polished, and sandblasted zirconia implants. The study found that rougher surfaces were favoured by osteoblasts (Bächle et al, 2007; Nothdurft et al, 2015).

The advantage of sandblasting is that hard materials like ceramic, glass, and silicon can undergo a uniform and delicate anisotropic abrasion. There are two negatives, though: First, due to inevitable particle contamination, sandblasting somewhat modifies the surface chemistry. Second, it will result in microscopic fissures in the surface (Han et al, 2017; Zhang et al, 2017).

1.1.2 Acid-etching

To remove the contaminants from the surface, an acid solution, such as hydrofluoric acid, nitric acid, or sulfuric acid, is used. With etching, the surface area will be greatly increased and a homogenous, consistent rough surface will be achieved (Zhang et al, 2017). For example, HF etching on the surface may improve osteoblast development and cell adhesion by boosting the expression of the genes for osteocalcin and collagen type I. (Bastian et al, 2008). The amount of fluoride on the surface has been found to positively correlate with pull-out findings (Gomez and Schmidt, 2007). Because zirconia is highly chemically inert and contains minimal silicon, prior tests demonstrated that its surface cannot be scratched (Oh et al, 2017). Recent studies, however, have shown that hydrofluoric acid (HF), sulfuric acid, nitric acid, and other solution acids can etch the surface of zirconia not only when heated, but can also do so at ambient temperature. (Quentin, 2016; Quentin et al., 2016). One advantage of etching is that there is no chance of material delamination because there is no force placed on the material (Hung et al, 2017).

Nonetheless, the surface's constituent parts will change (Quentin, 2016). Prior treatment, temperature, the composition of the acid combination, and the amount of time all affect how rough the surface is after etching (Monje, et al , 2016; Giner et al, 2018). The formation of these precipitates during HF etching on the surface emphasizes the importance of the cleaning process, as it is unknown how they will impair the bonding between the implant and bone (Quentin et al, 2016; Jang et al, 2018).

1.1.3 Sandblasting-acid etching

To increase surface roughness and remove contaminants, acid-etching and sandblasting are two of the most used modifications (Scarano et al, 2017). In the nanoscale, submicrometer, and micrometer scales, diverse topographies can be produced on zirconia surfaces by adjusting parameters such particle size, etching time, and temperature (Scarano et al, 2017; Velasco et al, 2019). Two or more sizes of secondary many pit foveae developed by acid etching can be seen on the basis of the irregular fluctuation created by sandblasting (Velasco et al, 2019). Sandblasting creates pit foveae of greater size, which serve as attachment points for cells and direct cell adhesion, extension, and differentiation (Bergemann et al, 2015). The cells' point-like contact with the microscopic pits created by acid etching stimulates cell response (Kim et al, 2015). The combination of the two elements raises the level of focal adhesion and eventually encourages the growth of bone around the implant (Bergemann et al, 2015). Hiroshi et al. did a study (Ito et al, 2013). Suggests that enhancing MC3T3-E1 cell proliferation and differentiation by sandblast-etching micro- and nano-topographies on TZP is a viable method.

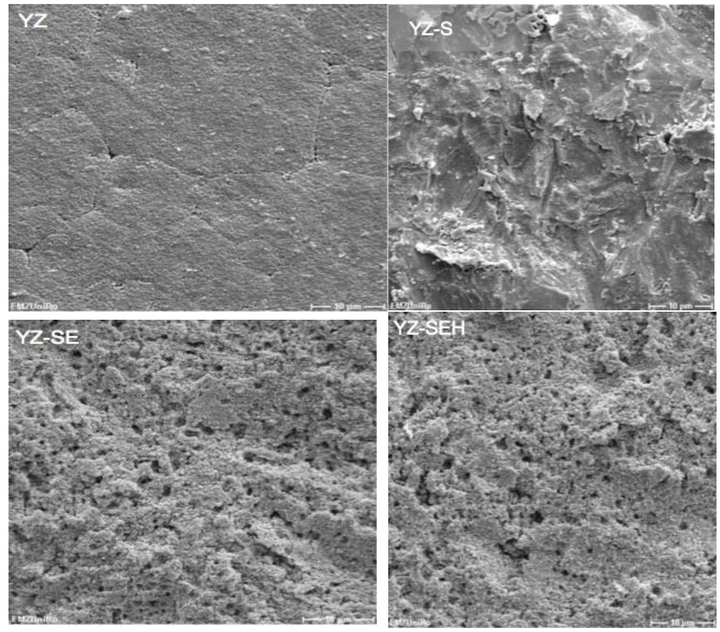

Figure 1: In comparison to machined zirconia, the surface topography of yttria-stabilized zirconia following sandblasting (YZ-S), acid etching (YZ-SE), and heat treatment (YZ-SEH) (YZ), taken from with permission (Bergemann et al, 2015).

1.1.4 Selective infiltration etching (SIE)

Unlike classical etching, a novel technology firstly reported by Aboushelib called selective infiltration etching can create a wide range of nano-topographies by injection-moulding on the surface of zirconia (Aboushelib et al, 2007). A special infiltration glass covered on the surface of zirconia is heated to its glass transition temperature (El-Ghany and Husein Sherief, , 2016). Then, the surface tension and capillary force caused by the diffusion of molten glass between the grain boundary will result in the separation of the grain (Aboushelib et al, 2007). Finally, while cooled to room temperature and placed in the acid, the glass between the grain boundary will be etched by acid, exposing the nanoscale porous structure (Aboushelib et al, 2010). Zirconia's entire surface is chemically similar, hence the creation of a different surface texture occurs on a nanoscale without causing component loss or escalating tiny surface roughness (Alagiriswamy et al, 2020).
In addition, the shape and distribution of the pits can be altered by varying the glass' composition, temperature, and heating time (Mostafa et al, 2018; Aboushelib et al, 2013).

By selective infiltration etching, Aboushelib et al. successfully changed the dense, nonretentive surface of zirconia implants into a nanoporous surface. Because cell quantity and size were substantially higher on SIE treated zirconia surface than on polished zirconia surface, nanoporous zirconia surface appears to boost cell development and attachment compared to polished zirconia surface (Mostafa et al, 2018). Ana-Maria Stanciuc et al. discovered that the surface of ZTA with SIE-created micro-roughness, fluorine enrichment, and nano-porosity has an additive effect on human osteoblast maturation (Stanciuc et al, 2018). SIE has a number of benefits: No new surface flaws are created, there is great flexibility in choosing the microtopography pattern, and it is possible to scale up to mass producing components with complicated geometry (Nassif and Rifai, 2018).

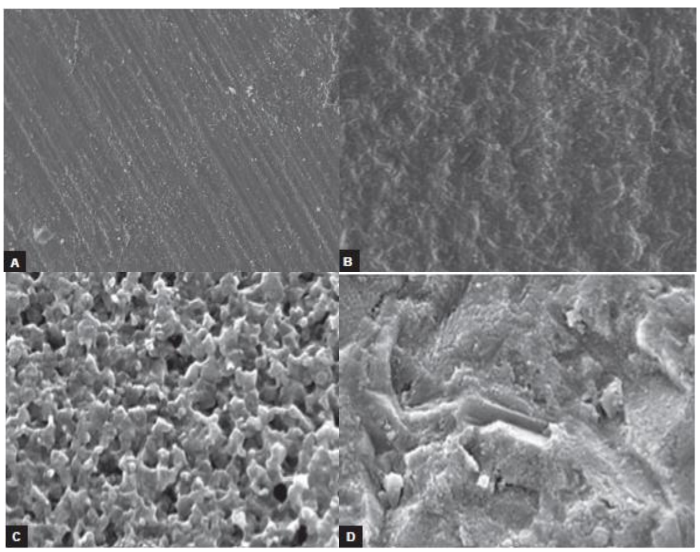

Figure 2: As a result of the AS group's polishing process, the surfaces shown in (A) and (B) have uniform densities and lines; (C) has a nanoporous SIE zirconia surface with valleys; and (D) has zirconia that has undergone ROC treatment to show the impact of silica on the surface. taken from with permission (Nassif and Rifai, 2018).

1.1.5 Laser

Due to its accuracy, great efficiency, and excellent controllability, laser is now commonly used for surface modification of zirconia implant materials (Gaggl et al, 2000). Laser treatment may create a variety of patterns on the zirconia surface in a controlled manner, such as micrometer holes and nanometric structure (Nayak and Dahotre, 2002). Power input, energy, pulse length, and the characteristics of the target material all play a role in determining laser topography (Nayak and Dahotre, 2002; Nayak et al, 2003). The amount of power input, for instance, affects the maximum temperature and cooling rate. The length of an interaction affects the interactions between phases (Götz et al., 2004). Since the heating and cooling rates are so fast, the microstructure may have a refined microstructure, extended solid solubility, and incomplete surface chemical reactions (Nayak and Dahotre, 2002). Unlike other treatments, laser modification can remove surface layers while posing no contamination risk due to no direct contact between the material and the laser (Smalley, 2011). Also, laser treatment increases the quantity of hydroxyl groups on the surface, which promotes surface wettability (Smalley, 2011; Romanos et al, 2009). Certain investigations have shown that insertion torque values were higher in zirconia implants treated with lasers than in nongrooved sandblasted implants (Delgado et al, 2014). There are numerous types of lasers available nowadays, including fiber lasers, femtosecond lasers, CO_2 lasers, and Nd:YAG lasers, each has its own distinct features and applications (Delgado et al, 2015; Di Matteo et al, 2016).

1.1.5.1 Fiber laser

The benefits of fiber lasers include their stability, high-energy beam, and short wavelength (1000-1100nm) with little spatial variations (Delgado et al, 2015). A fiber laser can produce many 2 μm wide grooves on the surface of zirconia implants with no effect on nanostructure (Yasuno et al, 2014). According to studies, the average BIC of the fiber laser group is 4.2 times greater than the smooth surface, and the average RTQ of the former is approximately 2.4 times greater than the latter, indicating the biological enhancement of laser treated zirconia implants. The morphology of osteoblast-like cells was altered by the application of a fiber laser to the surface of zirconia, which also markedly increased calcification and cell multiplication (Yasuno et al, 2014).

1.1.5.2 CO2 Laser

A gas laser with a low frequency and low photon energy is a CO2 laser (Stübinger et al., 2008). It is a form of thermal processing and is mostly employed in cutting and surface preparation (Siqueira et al, 2015). It is possible to focus the beam into a 100 um spot by using a lens with a low focal length (Cunha et al, 2022). However Stübinger et al. (2008) claim that the laser causes brittle rims and surface oxidation. CO2 laser is used by HAO et al. (2005) to alter the zirconia's surface characteristics. They show that the CO2 laser's increased wettability properties are principally caused by an increase in surface energy, especially the polar component, which is governed by microstructural changes (Hao et al, 2005). Microstructural examinations of the surfaces show that at low laser energies, the crystal structure undergoes reorientation, which is followed by the emergence of a hexagonal structural configuration. Cell formation begins for samples heated to 1.6 kW/cm2 when melting first appears on the surface (Park et al, 2012). Following this state, which corresponds to the maximum surface energy, there is a decrease in surface energy because a uniform cellular structure has developed (Cunha et al, 2022).

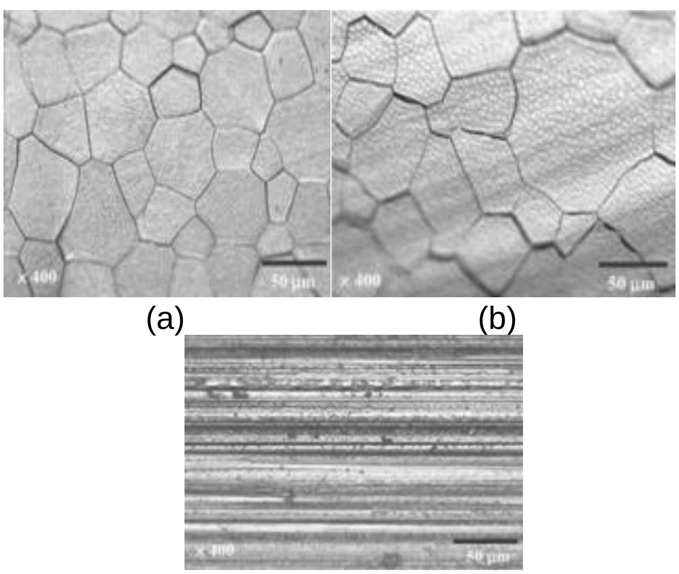

Figure 3 The morphology of (a) untreated YPSZ and (b) YPSZ treated with CO2 lasers at power densities of 1.80 kW/cm2 and (c) 2.25 kW/cm2 is shown in an optical image. This passage was copied from with permission (Hao et al, 2005).

1.1.5.3 YAG laser

Aside from CO2 laser, surface patterns can be accurately generated by regulating the pulse repetition rate of a postoperative neodymium-yttrium-aluminum-garnet (Nd:YAG) laser. The pulse repetition rate of a Nd: YAG laser can be regulated electronically, allowing precise production of predefined patterns (Di Matteo et al, 2016). Because of the lower wavelength of the Nd:YAG laser, the beam can be focussed to a smaller spot size than the CO_2 laser (Beketova, et al, 2016; Suzuki, 2015). The operation of CO_2 and Nd:YAG lasers is mostly thermal in nature, with the focusing optics directing a predetermined energy density into a focused area on the workpiece (Ciupak et al, 2021).

The absorption of radiation at the surface of a material elevates its temperature prior to ablation, resulting in melting at the surface. The material vaporizes as the temperature rises, and finally solidifies when the temperature falls (Roitero et al, 2017). Hence, when a focused laser beam interacts with a material surface, the set of steps involved in the formation of new surface topography are melting, melt motion, evaporation, and solidification (Suzuki, 2015; Roitero et al, 2017).`23ws Kakura et al. (2014) use YAG laser irradiation to cure the zirconia implant (Rough zirconia implants, R-ZrIs). The BIC ratio for R-ZrI was approximately 1.25 times greater than for smooth zirconia implants (S-ZrIs) on the cortical bone side (Kakura et al, 2014).

2.1.5.4 Femtosecond laser

Femtosecond laser, as a type of pulsed laser, improves surface roughness, lowers the existence of residual elements, and the final surface preserves its properties indefinitely. It is also a technology with the potential for automation and thus repeatability (Sugioka et al, 2014). It offers a great level of flexibility and precision in surface design (Jonuauskas et al, 2019). It reduces the presence of leftover elements as compared to other laser treatments (Rizvi, 2003). Microgrooved zirconia implants that performed well in vitro and in vivo were created using femtosecond laser micromachining (Park et al, 2012; Beketova et al, 2016). The osteogenic response of human mesenchymal stem cells can be improved by adjusting the width, height, and spacing of microgrooves made by femtosecond lasers in biomaterials, such as bioinert ceramics (hMSCs) (Kim et al., 2015; Nadeem et al., 2013). In a work by Ana-Maria Stanciuc, a femtosecond laser was used to carve out pits on the surface of zirconia in order to produce a variety of micropatterns. They find that the pattern with dimensions of 30 m in diameter and 10 m in depth was responsible for the greatest osteoblastic hMSC commitment (Oyane et al, 2016). A fascinating alternative to traditional surface treatments for zirconia implants is the femtosecond laser because of its accuracy and minimal impact on the surrounding area (Stübinger et al., 2008).

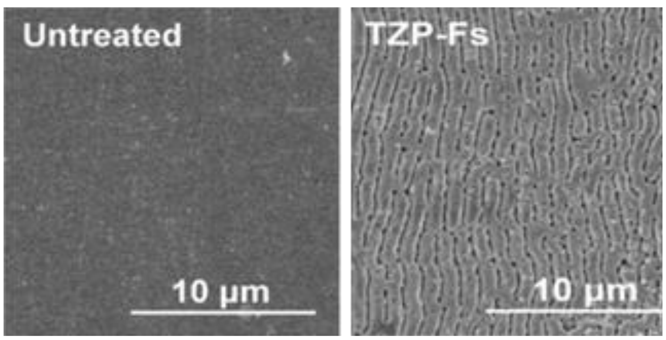

Figure 4: Surfaces of the untreated Y-TZP sample and the TZP treated with femtosecond were captured in SEM images. Extracted from (Oyane et al, 2016).

1.2 Modification of Surface Chemistry

Surface chemistry, including wettability, chemical composition, and crystallinity, is equally important in addition to surface topography because it encourages cell responses including adhesion and proliferation, which leads to a higher contact zone at the bone-implant interface (Duraccio et al, 2015). Applying functional groups to the surface to improve surface chemistry is referred to as "modifying surface chemistry" (Kligman et al, 2021). For instance, biofunctionalization on the zirconia surface can change the material from bioinert to bioactive, resulting in a surface with greater bone remodeling activities and a response to bone formation (Duraccio et al, 2015; Aita et al, 2009).

Table 2: Modification of surface chemistry

Method	Charecterstic	References
UV treatment	Transform from hydrophobic to hydrophilic Reduced the atomic percentage of surface carbon	(Aita et al, 2009; Rizvi, 2003)
Biofunctionalization	Grafts biomolecules on surface Proteins, enzymes, peptides, etc	(Nadeem et al, 2013; Wang et al, 1997)

1.2.1 UV treatment

Certain authors believed that UV would have a similar impact on zirconia implants and increase the bioactivity around them based on prior studies that showed that osseointegration of titanium implants with ultraviolet therapy was greatly improved due to the action of super-hydrophilic (Aita et al, 2009; Wang et al, 1997).

Researchers have discovered a connection between this phenomenon, also known as "UV light-mediated photofunctionalization," and the development of hydrophilicity, alteration of the surface's electrostatic properties, and photochemical and photocatalytic removal of hydrocarbons from the material's surface (Tuna et al, 2015). UV light treatment converted the surface of zirconia from hydrophobic to hydrophilic in a dose-dependent manner, while also lowering the atomic percentage of surface carbon (Brezavek et al., 2016; Altmann et al., 2013). Another mechanism suggested is that UV light-induced surface oxygen vacancies at bridging oxygen sites facilitate dissociative water adsorption. Moreover, zirconia photocatalytic activity modifies the chemistry of water's surface, causing wetting (Wang et al, 1997). In a recent study, Wael Att, et al. (2009) found that zirconia treated with UV can boost osteoblasts' bioactivity in terms of attachment, proliferation, and ultimately mineralization. Its biofunctionalization is related to the hydrophilic conversion of zirconia surfaces by UV light-catalyzed reaction and the progressive removal of hydrocarbons (Att et al, 2009).

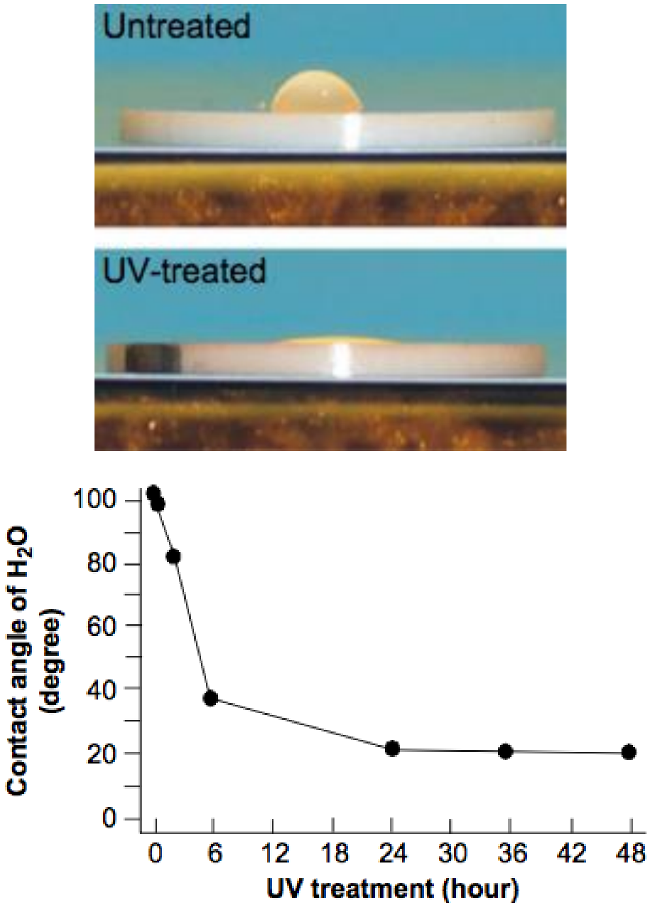

Figure 5: Zirconia disk surface morphology and hydrophilicity. taken from with permission (Aita et al, 2009).

1.2.2 Biofunctionalization

When biomolecules like proteins, enzymes, and peptides are grafted onto surfaces to change their biochemical characteristics, the resulting changes in the biological responses are referred to as biofunctionalization, also known as biomimetic surface modifications. 2014 (Hsu et al.). Nowadays, biofunctionalization is regarded as a successful method for changing the composition, structure, and/or morphology of surfaces without affecting the general qualities. In particular, covalent bonding of biomolecules on surface has become essential for various tactics such as assay technologies, biosensors, imaging devices, and therapeutics in order to produce bioactivity on biomaterials. (Khatayevich et al., 2010; Hanawa, 2011). RGD sequence, other oligopeptides, proteins, aptamers, and even numerous peptides with cooperative activities are just a few examples of the complex biomolecules that have been attached to metal surfaces (Chen et al, 2013; Rocas et al, 2015). However, the possibility of chemically biofunctionalizing other biomaterials of more recent interest in dentistry, notably those based on zirconia, is less understood. However the approaches of biofunctionalization are developed for titanium materials with encouraging results.

1.3 Coating

The goal of coating, a typical surface modification technique, is to enhance the surface characteristics of biomaterials, which primarily serve as strong mechanical supports but also need to have improved surface characteristics to facilitate osseointegration (Xuereb et al, 2015). Coating has the benefit of forming a solid interface with bone tissue and providing enough mechanical stability to sustain the stresses used during implantation (Junker et al, 2009). Moreover, coatings must to have controlled rates of dissolving in bodily fluids and perhaps function as a medication delivery mechanism (Piotrowski et al, 1975). However, the major problem with surface coating treatment is that the bond force between coatings and implants is insufficient, and in long-term applications the coating tends to gradually separate from the implant (Junker et al, 2009). Several coating materials are available to make a surface bioactive. Today, bioglass, hydroxyapatite (HA), calcium phosphate (CaP), nanostructure coating, and various types of bioactive ions are used as coating materials for zirconia implants (Xuereb et al, 2015; Bosetti et al, 2001).

Conclusions

Zirconia is gaining popularity as a ceramic biomaterial for dental implant applications because of its biocompatibility and good mechanical qualities. Many investigations have been done to alter the dental implant surface's osseointegrative qualities. Even if there are occasionally inconsistent outcomes, many researchers are working to enhance their individual surface modification methods with a more thorough and in-depth investigation to understand the underlying process underpinning surface attributes and cellular response. The reliability of zirconia implants in medical treatment applications is anticipated to be improved with time by surface alterations. The future studies might further focus on innovative surface treatments 0f titanium dental implants, including self-assembled monolayer (SAM), 3D printing, and thin silica coatings to optimise bioactivity and biocompatibility.

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