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Ceramic Materials as an Alternative to Titanium for Dental Implant Fabrication

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Abstract

Titanium is the gold standard material to produce dental implants from more than 30 years, showing high success rate in different clinical scenarios. Zirconia implants were recently introduced to overwhelm some aesthetic and biological problems that can arise from titanium. Preclinical studies show that, from a mechanical point of view, zirconia may be a suitable substitute for titanium in implant fabrication. Three-dimensional finite element analysis (FEA) models found no difference between titanium and titanium-zirconium alloy implants, neither for early nor conventional functional loading. Nevertheless, zirconia presents the same osseointegrative properties of the titanium, even if the few clinical studies show survival and success rates slightly inferior for zirconia implants comparing to titanium ones, and long-term follow-ups are missing. For these reasons, the majority of authors agree to be cautious for proposing zirconia implants as widespread substitute of titanium implants.

Keywords: dental implants, one-piece implant, zirconia, zirconia implant

1. Introduction

Commercially pure (CP) titanium is the gold standard material used to produce dental implants over more than 30 years [1], showing a high success rate in different clinical scenarios [2–4].

Nevertheless, titanium implants may present some esthetic issues: the gray color of titanium implant may be visible in the presence of thin peri-implant tissue, leading to esthetic concern, especially in the anterior area [5]. This aspect can get dramatically worse In case of peri-implant

mucosa recedes over time. The availability of a “white” implant may be crucial in those clinical cases in which esthetic result is mandatory.

Furthermore, titanium particles due to wear and corrosion products may be released in tissues close to implants, and they were found in regional lymph nodes [6]. In some cases, this may lead to host reaction or sensitization [7]. Some cases of allergic reaction to titanium are documented, even if rare [8, 9]. So, using some nonmetallic material as an alternative to the titanium implant may be useful and, in some cases, critical. Last but not least, always more patients request completely metal-free prosthetic reconstructions.

Ceramic implants were introduced to overwhelm some esthetic and biological problems that can arise from titanium. The first ceramic dental implant was made from alumina (i.e., aluminum oxide, Al_2O_3) between 1960s and 1970s, and that was the only ceramic material used until recently. However, alumina presented some biomechanical problems (like low fracture toughness), and it was then completely abandoned and replaced with zirconia that is nowadays the only alternative ceramic material to titanium for dental implants (**Figure 1**) [5].

The aim of this chapter is to review the existing literature regarding zirconia dental implants, highlighting the strong points and stressing the so far unclear aspects.

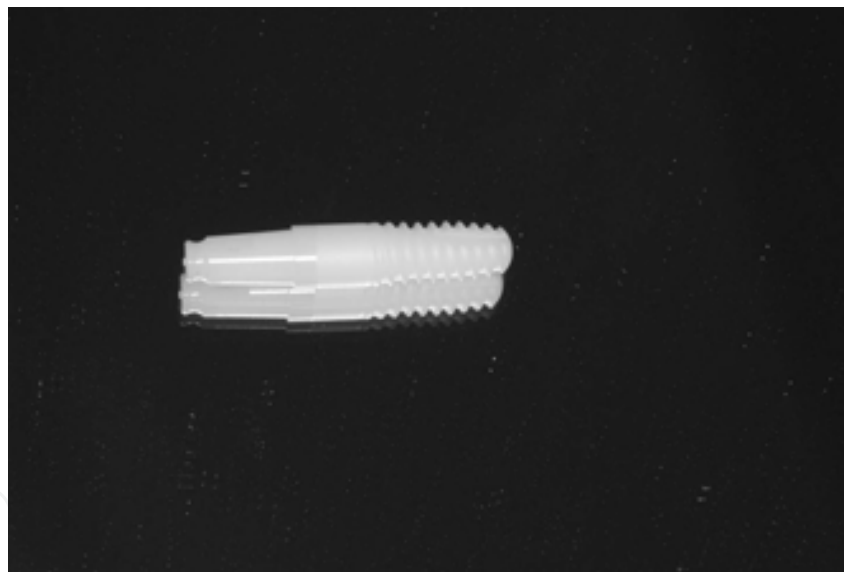


Figure 1. A one-piece zirconia implant (courtesy of Prof. Andrea Enrico Borronovo, University of Milan).

2. Zirconia

2.1. Mechanical aspects

Zirconia (zirconium dioxide, ZrO_2) is a white crystalline oxide of zirconium. It is polymorphic in nature, transforming its crystalline reticule from monoclinic (at room temperature) to

tetragonal to cubic at increasing temperatures. By adding some oxides to zirconia, it is possible to stabilize the tetragonal and/or cubic phases. The so-called *partially stabilized zirconia (PSZ)* consists mainly of a cubic phase, with monoclinic and tetragonal zirconia as minor phases. By adding 2–3% of yttria (yttrium oxide, Y_2O_3), it is possible to obtain a completely tetragonal zirconia, the so-called *yttria-stabilized tetragonal zirconia polycrystal (Y-TZP)*. The Y-TZP is the most performing zirconia from a mechanical point of view and the most used in dentistry to produce implants, implant abutments and frameworks for crowns and bridges.

Its interesting and in some cases unique mechanical properties are the reasons why zirconia is often called “ceramic steel”: a high corrosion and wear resistance, high Young’s modulus (200 GPa), a very high flexural strength (up to 1200 MPa), a high fracture toughness and a polymorphic behavior [10]. The latter is probably the most interesting aspect: zirconia may adapt the three-dimensional disposition of the structure when some energy is provided, that is what happens in a crack initiation. In proximity of the crack, the energy changes the phase locally, turning the reticule from tetragonal to monoclinic. This phase transformation happens with an increase in volume (3–4%): the expansion of the crystals opposes to crack propagation and prevents macroscopic failure, enhancing fracture toughness. This mechanism is known as *transformation toughening* [11, 12].

Such a phenomenal mechanism of action against crack propagation has been questioned because of the so-called *low-temperature degradation process*, a sort of aging of zirconia. It seems that in the presence of water, the yttrium ions can be leached, and their stabilizing effect can be lost [13]. In that case, a spontaneous irreversible transformation from the metastable tetragonal phase to the stable monoclinic phase can occur on the surface of zirconia. Such a stabilized monoclinic phase does not have the capacity anymore to rearrange the crystalline reticule and so to oppose to an incoming fracture. However, the impact of this issue on the long-term clinical behavior of zirconia prosthetic components and implants is still unclear [5].

2.2. Biological aspects

The biocompatibility of zirconia is well established from both in vitro and in vivo studies [14]. In-vitro tests were conducted on various cellular lines, such as osteoblasts, fibroblasts, lymphocytes, monocytes, and macrophages, showing no cytotoxic effects. In vivo tests also showed no cytotoxicity in soft (connective) or hard (bone) tissues [12]. For this reason, its use as a biomedical implant (e.g., in orthopedic surgery) is widespread [15].

3. Mechanical properties of zirconia implants from experimental and clinical data

Considering the difficulty of analyzing the mechanical outcome of implants in clinical scenarios, preclinical studies are fundamental to accomplish this issue. Different in vitro studies evaluated the biomechanical behavior of zirconia implants with prosthetic reconstructions. The fracture strength of zirconia crowns on zirconia implants was compared to that of

metal-ceramic crowns on titanium implants, in an upper central incisor model. No difference was found between implants, with and without cyclic loading before fracture test [16]. The same authors also showed that preparation of zirconia implants to receive prosthetic crown may negatively affect the fracture strength, even if it was still in an acceptable clinical range [17]. Another in vitro study evaluated the fracture strength of zirconia implants in comparison with that of titanium implants under a 130° angled load, simulating that of an upper central incisor. Despite the high dispersion of fracture loads (typical of ceramic materials), the mean fracture strength ranged within the limits of clinical acceptance [18].

With caution, it is possible to affirm that from experimental preclinical studies, the biomechanical behavior of zirconia implants does not differ from that of titanium implants. So, no biomechanical contraindications are present for clinical use of zirconia implants [12].

The majority of clinical studies focused on achieving and maintaining osseointegration in time. In these studies, the main cause of failure is represented by marginal bone loss and/or the loss of osseointegration (see below). However, one clinical study considered just implant fracture as cause of failure: the survival rate was 92.5% after about 5 years, the loss of osseointegration has not been taken into account [19].

4. Osseointegration

The capacity to achieve osseointegration is the most investigated aspect regarding zirconia implants. To evaluate implant osseointegration, the following parameters are widely used:

- bone-to-implant contact (BIC) value;
- torque removal force;
- crestal bone loss (CBL).

The BIC value is usually studied using histomorphometry on histological sections. The torque removal force is considered a biomechanical measure of osseointegration: the greater the force is required to remove implants, the greater the strength of osseointegration. CBL is a clinical parameter related to the maintenance of osseointegration in time, and so it is related to survival and success rate of implant therapy (see Section 5).

One of the first animal studies investigating the osseointegration of zirconia implants was conducted in a rabbit model [20]. After 1 month from the insertion, the histological analysis showed newly formed bone close to the implant surface, affirming the osteoconductive property of zirconia. Titanium and zirconia implants were inserted in monkeys and after 3 months were functionally loaded for 5 months. The histological analysis performed later revealed no difference in osseointegration [21]. Titanium, machined zirconia, and surface-modified zirconia implants were inserted into rabbit. No difference in the removal torque was found between titanium and surface-modified zirconia, but machined surface zirconia implants performed badly. Such results seem to suggest that a modification of the zirconia surface is recommended to increase the bone tissue response [22]. Titanium, machined

zirconia, and sandblasted (rough) zirconia were inserted into the maxillae of miniature pigs, and then removed. The removal torque test revealed that rough zirconia implants can achieve a higher stability than machined implants [23]. A detailed analysis performed using scanning electron microscopy (SEM) [24] and histomorphometry [25] revealed no difference of osseointegration between titanium and zirconia implants inserted into minipigs. A study compared the osseointegration of zirconia and titanium implants in dogs, indicating no difference in BIC values between the two types of implants [26]. Another study performed a similar analysis in pigs. After 4 weeks from the insertion, no difference in terms of BIC was found between zirconia and titanium implants (**Figure 2**) [27]. Another histomorphometric study conducted on dogs found no difference in osseointegration and tissue response between titanium, and coated and noncoated zirconia implants [28]. Different implants (titanium and zirconia) used in pigs showed no significance difference in BIC values [29]. Calvo-Guirado et al. [30] found no difference in BIC values between zirconia and titanium implants in an animal model, and they concluded that both implant types produce good osseointegration.

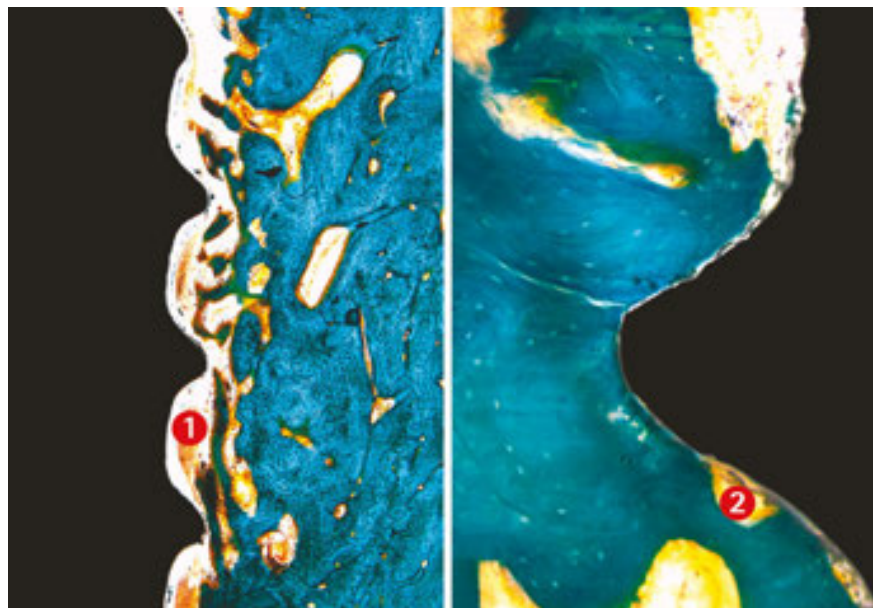


Figure 2. Histological section of zirconia implants inserted into a minipig. 1: neo-osteogenesis; 2: osteoblasts on the implant surface (courtesy of Dr. Mai, University of Dresden).

From the totality of animal studies, it is possible to conclude that zirconia is an osseoconductive material [14], and therefore it can be utilized as a material for dental implants [31].

5. Crestal bone loss around zirconia implants and survival and success rate

As zirconia implants have been used over relatively few years, a few clinical studies with limited follow-up are available. Furthermore, the results are not easy to compare. It is important to keep this statement in mind analyzing the following studies and the consistent

conclusions. The largest prospective clinical study (831 implants in 378 patients) reported a success rate of 95% after 5 years [32]. The success rate of the acid-etched implants was slightly higher than that of coated and noncoated implants. A 1-year follow-up case series analyzed 56 implants (12 in upper jaws and 44 in mandibles) inserted into 28 patients. A survival rate of 98.2% was found, with an average marginal bone loss of almost 2 mm, which appears quite high, lowering the success rate to 60% [33]. A prospective study with a very small number of cases found a success rate of 100%, with a minimal bone loss after 4 years (0.6 mm) [34]. An *in vivo* study found a greater bone loss around zirconia implants in respect to titanium implants after 12 months of function. However, no difference in the survival rate was recorded [35]. A recent systematic review of 13 studies (maximum follow-up of 4 years) concluded that the survival rate of zirconia implants ranges from 67.6 to 100% [36].



Figure 3. The radiographic control of prosthetic crown cemented on a zirconia implant (courtesy of Prof. Andrea Enrico Borgonovo, University of Milan).

In conclusion, from the available data the osseointegration of zirconia implants seems not to be a problem (**Figure 3**) [37]. Nevertheless, survival and success rates of zirconia implants are inferior to those of titanium ones [13]. For this reason, the majority of authors [12] remain

cautious and agree that further follow-ups are needed to evaluate the long-term success rates, before a routine use of zirconia implants can be recommend widely.

6. Zirconia and surrounding bone

As the stiffness of zirconia is twice that of titanium, an excessive stress on the trabecular bone around the implant may be expected. Various mathematical studies were performed to analyze the biomechanical behavior of the surrounding bone. One of the first studies in this field compared the response of surrounding bone around titanium and zirconia root-shape implants. No difference emerged from finite element analysis (FEA) [38]. A three-dimensional FEA found no difference in the stress distribution of bone between two versions of the same implant: one made of titanium and the other one made of zirconia [39]. A numeric stress analysis was performed to reproduce the mechanical behavior of the bone around zirconia and titanium implants [40]. The numeric model was also validated from the experimental point



Figure 4. The experimental validation of numeric model of a zirconia implant (from Mobilio 2013).

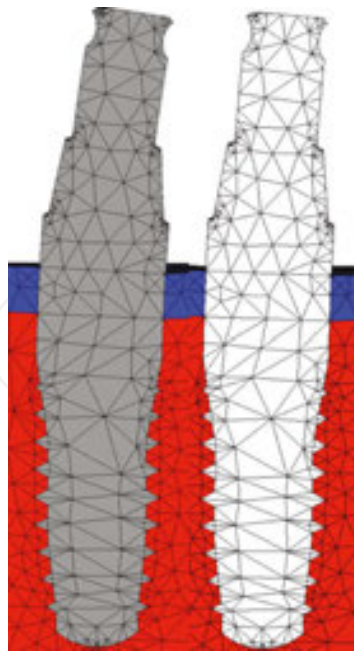


Figure 5. Deformed shape of the titanium (on right) and zirconia implants (30× magnification): the titanium implant shows a higher head displacement in the x -direction (from Mobilio 2013).

of view (**Figure 4**). The results showed that stress states generated in the bone by the two implant types were very similar; therefore, from a mechanical point of view, zirconia is found to be a feasible substitute for titanium. But more interestingly, results showed that the two implants moved differently: titanium implants generate higher stress on the cortical bone, whereas zirconia implants produce stress mainly in the trabecular bone. This different behavior is directly related to different Young's modulus values of the two materials: while titanium leans against the cortical bone and its exterior part is more prone to bending under load, zirconia is too stiff to bend and transmits stresses along its axis down to the trabecular bone, thus moving more as a rigid body (**Figure 5**). This difference in motion between the two implants is important considering crestal bone loss. Bone resorption around implants is a common phenomenon that begins at the cervical level and can progress in the apical direction. No conclusive data are available on contributing factors involved in such a bone loss, but concentration of stresses around the neck of the implant due to functional and nonfunctional loads may be one such factor. In this view, it can be speculated that decreasing the stress concentration at the cervical level may reduce the effect of mechanical factors on crestal bone loss.

Other FEA studies found similar results. The model of a maxillary overdenture on four implants with ball attachments revealed no difference in the stress and strain values in peri-implant bone, using titanium or zirconia [41]. A three-dimensional FEA model found no difference between titanium and titanium-zirconium alloy implants, neither for early nor conventional functional loading [42]. A study found difference in bone behavior depending on the macrogeometry of the zirconia fixture [43].

7. Peri-implant soft tissue response

Zirconia is advocated to have high biocompatibility and to have no adverse effect on the surrounding tissues (**Figures 6 and 7**) [44]. Many studies evaluated tissue response to zirconia, concluding that zirconia has the ability to interact with peri-implant soft tissues (**Figure 8**) [14]. The low bacterial colonization typical of the zirconia surface maybe plays a role in this high biocompatibility [12]. In a randomized-controlled trial (RCT), both titanium and zirconia one-piece implants supporting overdentures were evaluated [35]. Even if the crestal bone level changed greatly, no difference in clinical parameters (probing depth, bleeding index, plaque index, etc.) was found around the two types of implants after 12 months of function.



Figure 6. Clinical aspect of the abutment part of zirconia implant before cementation of crown (courtesy of Prof. Andrea Enrico Borgonovo, University of Milan).



Figure 7. Clinical aspect after finalization (courtesy of Prof. Andrea Enrico Borgonovo, University of Milan).

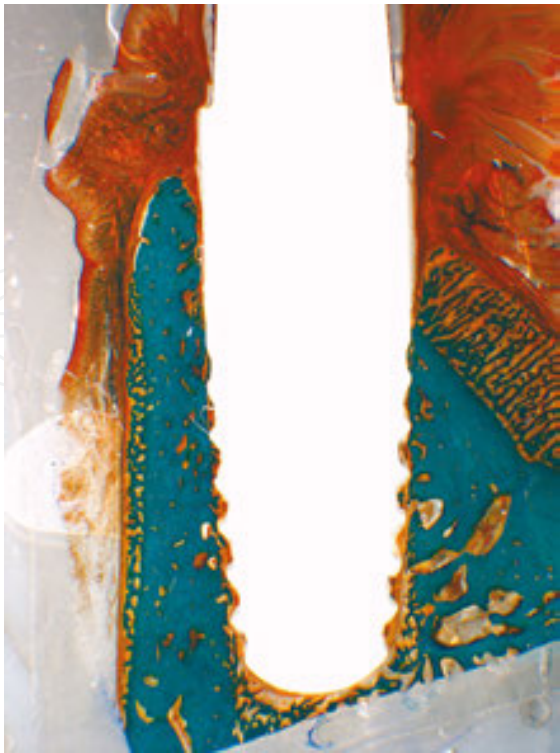


Figure 8. Histological section of zirconia implant inserted into a minipig. The tight connection of the soft tissue to the implant surface is shown (courtesy of Dr. Mai, University of Dresden).

8. Available products

Product	Manufactory	Web site
WhiteSky	Bredent Medical & Co	http://www.bredent-medical.com/en/medical/product-informations/2002/14/
Ceraroot	Oral Iceberg L.L.C.	http://www.ceraroot.com/professionals/products/implants
Axis	Axis Biodental	http://www.axis-biodental.ch/biodentalnew.php?id_structure=7&portail=2&langue=en
Y-TZP BIO-HIP Sigma®	Incermed	http://www.incermed.ch
Z-Look3	Zirkolith	http://zsystems.com/en/doctors/products-z5-zirkolithr-ceramic-implants/z5m-lblc-zirkolithr-implant.html
Zit-Z	Ziterion	http://www.ziterion.com

Many zirconia implants are commercially available. The most famous products are listed in **Table 1**. Even if all available implants are constituted by Y-TZP, the surface characterization (regarding in particular some parameters such as carbon contamination and phase transfor-

mation) is far to be the same for all products [45], and few independent data are available on this issue. Contrary to CP titanium, the name “Y-TZP” is often insufficient to characterize the material, and the clinician must pay attention to the details of the selected product.

9. Conclusions

Ceramic implants were introduced to solve some esthetic and biologic problems related to traditional titanium implants. Y-TZP has the biomechanical properties suitable to produce dental implants. To date, in vitro and in vivo studies have shown good results from a mechanical point of view. Furthermore, zirconia is an osteoconductive material, so achieving osseointegration is not a problem, and the simulation of stress distribution into the bone did not find essential difference from titanium. Unfortunately, long-term follow-ups are missing, so no solid clinical evidence is currently available to recommend routine use of zirconia implants or to replace titanium implants, which is still found to be the gold standard for dental implantology. So, even if zirconia implants are a good option from theoretical and experimental point of view, the clinical long-term response is not yet available. Almost all the authors agree to be cautious for proposing zirconia implants as substitutes of titanium implants for replacing teeth. Long-term, well-designed perspective clinical studies are needed to address the missing aspects of this undoubtful promising alternative.

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