

From titanium to zirconia implants

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Zirconium is a metal with the atomic number 40. Zirconium dioxide (ZrO_2) or Zirconia is a ceramic material without any metal properties. It is electrochemically inert causing no galvanising or electro current disturbance effects at an inter- and intracellular level. It is the most bioinert and biocompatible material currently available in the market, with no detected allergies or intolerances. The material exhibits lower surface free energy that leads to hydrophilic reduced plaque (biofilm) accumulation, so, less inflammation is expected leading to superior soft tissue health.

Zirconia fulfils highly desirable aesthetic results: healthy, pink and beautiful tissue can be created around an implant, with no tissue translucency. Its high aesthetics resembles natural tooth. Unlike titanium, it may stimulate bone growth in the long-term with ultimate osseointegration for both bone and gum. In addition to the white colour, a low modulus of elasticity and thermal conductivity have made zirconia implants a very attractive alternative to titanium in implant dentistry.¹⁻⁴

With its interesting microstructural properties, zirconia is the material of choice for the “new generation” of implants. Hashim et al. (2016) made a systematic review and evaluated the clinical success and survival rates of zirconia ceramic implants after at least one year of functioning.⁵ They concluded that in spite of the unavailability of sufficient long-term evidence to justify using zirconia oral implants, zirconia ceramics could potentially be the alternative to titanium for a non-metallic implant solution. This is also shown in the review made by Cionca et al. (2017), that through *in vitro* and *in vivo* studies, zirconia has managed to earn its place as a valuable alternative to titanium.⁶

Mechanical and physical properties

Zirconia though, is a totally different material than titanium. The thorough knowledge of implantology using titanium is not so easy to be transferred to zirconia, simply

due to different physical and mechanical properties of the materials. Knowledge of the potentials of the material is the key of success and the only chance to minimise failures. Zirconia (ZrO_2) is a highly biocompatible material, but it needs to osseointegrate and withstand masticatory force without fracturing. A good product needs to be fabricated that would fulfil all the necessary requirements in order to be successfully implanted.

ZrO_2 is stable at room temperature at a monoclinic phase. Doped by yttrium oxide, when it cools down from 1,173°C, a tetragonal phase stable at room temperature (metastable) is produced. This is the material used for implants. It is of major importance for the implant to be kept in the tetragonal phase to keep its mechanical and physical properties over time. It is well established that the stability of this phase is affected by several compositional parameters, including grain-size, processing conditions and quality control.

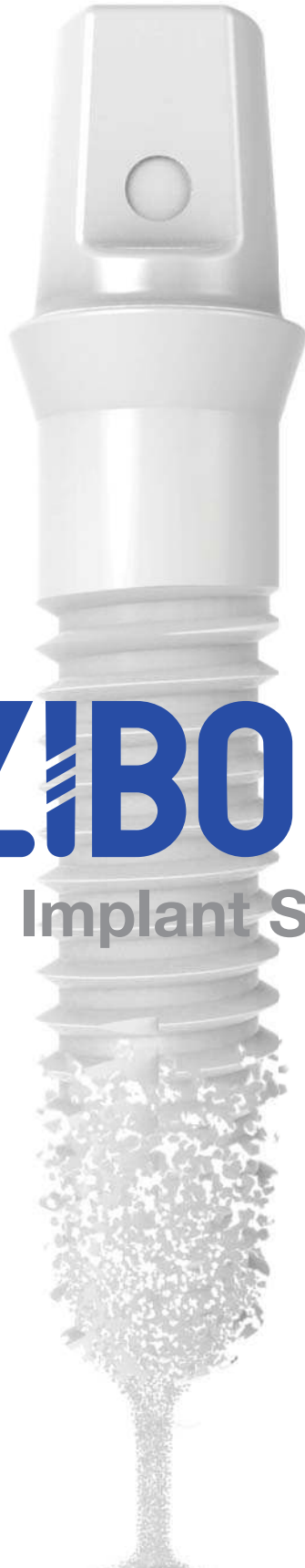
Purity or rather contamination with impurities, density and porosity of the final product as well as pre-sintering and sintering process and time are also some of these parameters. Environment or conditions (loading-temperature-humidity) in which the product will be used (it makes a difference whether zirconia is produced for a hip prosthesis or for dental implants) are to be kept in mind. And last but not least, handling of the material is of utmost importance.^{7,8} Lughy et al. (2010) suggested engineering guidelines for the use of zirconia as dental material.⁹


Producing zirconia implants

There are two ways of producing zirconia implants: through moulding and through milling of prefabricated rods. The first method produces implants with specific shape and specific low roughness on their surface. Milling of the rods on the other hand, is done either on partially or fully sintered zirconia. The fabrication of an implant through soft machining of partially sintered ZrO_2



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Ageing of titanium vs zirconia

Ageing of titanium implants is a not widely known phenomenon and starts four weeks after their production which decreases dramatically the osseointegration potential.^{15–18} Ageing of zirconia (Low Temperature Degradation LTD, i.e. the slow transformation of the metastable tetragonal crystals to the stable monoclinic structure in the presence of water or water vapour) on the other hand is quite well investigated.

Degradation rates at room or body temperature of Y-TZP ceramics are currently not available, and accelerated tests at intermediate temperature (100 to 300 °C) are the only basis for extrapolating an estimate of the transformation rate and, hence, of the product lifetime. This approach relies on the assumption that the transformation rate follows the same Arrhenius-like trend down to room/body temperature. Unfortunately, such extrapolation could lead to a significant error in estimating room/body temperature lifetimes.⁹ Still this is the method that is used in researches. Monzavi M. et al. (2017) examined 36 zirconia implants of four different brands and found that the effect of ageing was minimal in all systems.¹⁹ They suggested though that *in vivo* studies are needed to investigate the effect of mastication force on the extent of LTD and the influence of surface changes such as delamination of the grains on surrounding hard- and soft-tissue.

provides the advantage of easier milling than the fully sintered ZrO₂. It requires less milling time and causes less wear of the cutting tools.^{10,11}

In hard machining of fully sintered ZrO₂, no sintering shrinkage is expected and there is no need for a sintering oven. However, microcracks maybe introduced.¹⁰ Since diamond zirconia is known as the toughest material existing, only diamond tools are used for cutting sintered zirconia. The grinding of the fully sintered ZrO₂ causes a certain degree of transformation (from tetragonal to monoclinic phase) in the surface of this material.¹² When comparing the final surface of the soft machined ZrO₂ to the hard machined ZrO₂, it is expected that the former will have a more consistent final state, given that it is left intact (no sandblasting or grinding) after the final sintering.¹³

The implants that are produced need to be roughened in order to be osseointegrated. Question arises what is the optimal roughness and surface that is produced after it, in order for zirconia implants to be successfully osseointegrated in any of the aforementioned production methods. It seems that the rougher the body, the better the odds for osseointegration.¹⁴ This though should not be the goal for the head of the implant in case that it is visible in the mouth—it could favour bacteria colonisation. The best method to achieve the optimal roughness as well as the moment that this should be realised with respect to the material's properties is also not established. Finally, depending on the procedure, the roughened surface needs to be totally clean, free of all foreign bodies.

Still a certain degree of transformation from tetragonal to monoclinic phase can actually improve the mechanical properties of Y-TZP. Under stress, i.e. at the tip of a crack, the Y-TZP undergoes a phase transformation from tetragonal to monoclinic phase. This phase transformation results in a 3 to 4 per cent volumetric expansion inducing a compressive stress in the area of the crack and theoretically prevents crack propagation.¹ An implant which exhibits phase transformation in case of microcracks and high forces is desirable. Still it is not sure whether the already existing microcracks that are produced (for instance, during handling) during mastication or parafunctional activities, don't propagate, leading to a possible fracture.

One- vs two-piece zirconia implants

Zirconia appears in two varieties, one- and two-piece implants. One-piece implants offer the absence of a microgap between implant and abutment which seems to be of benefit. The surgical placement of the implant, though may not always meet the prosthodontic requirements and angled abutments in order to correct misalignment, is not common. Secondary corrections of the shape by grinding must be avoided, as this severely affects the fracture strength of zirconia.²⁰ Protection by use of splints is also required, though not always possible. So, two-piece implants were

designed. Designing a zirconia implant should be based on material properties and should simplify surgical and prosthetic steps for the doctor. Size limitations should be considered, in order to produce an implant that is not prone to fractures. A clinical study by Gahlert et al. (2012) showed a marked tendency of one-piece implants with a narrow diameter (3.25mm) to fracture, with a percentage that reached 92 per cent of the fractured implants.²¹ Threads and shape of implants should be designed according to the needs, always with respect to material.

Size and shape precautions should also be applied to the implant head in order to avoid the risk of creating microcracks during implantation. The implant head if positioned at the gingival level or even higher, could eliminate the need for a second surgery, as well as to bypass the bacterial growth in the gap between implant and abutment. The decision of choosing between a one- and a two-piece implant could be influenced by the design of the implant, the available space to be installed, and the prosthetic rehabilitation that follows.

Implant-abutment connection

Connection of the abutment with the implant is performed by three ways: either by screwing, cementing, or

even as a combination of both. When screwing, the material of the abutment and the connecting screw is of crucial importance for the implant to be intact. As a consequence from titanium knowledge, screwing an abutment made from the same material as the implant was a "natural" step. Screwing though zirconia inside a zirconia, unlike titanium, cannot result in a tight connection, because of the stiffness of the material. This loosening could possibly result in fracture and if this happens to the implant, it could jeopardise everything. In case of abutment failure, one should estimate the convenience of removing the abutment screw.

A recent *in vitro* study by Preis et al. (2016) comes to strengthen the aforementioned performance of different implant-abutment connections, was investigated in six groups of different two-piece zirconia implant systems.²² In group 1, the abutments were cemented to an alumina-toughened zirconia implant. In group 2, the abutments were screwed with a carbon fibre reinforced polymer screw on an alumina-toughened zirconia implant. In the remaining four groups, the abutments were screwed with titanium screws on tetragonal zirconia polycrystalline implants. A standard screw-retained titanium implant served as the control. The bonded zirconia system and the titanium reference survived without any failures. Screw-retained zirconia systems showed fractures of abutments and/or implants,

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partly combined with screw fracture/loosening. Failures concerning the abutment/implant region around the screw, indicate that the connecting design is crucial for clinical success.

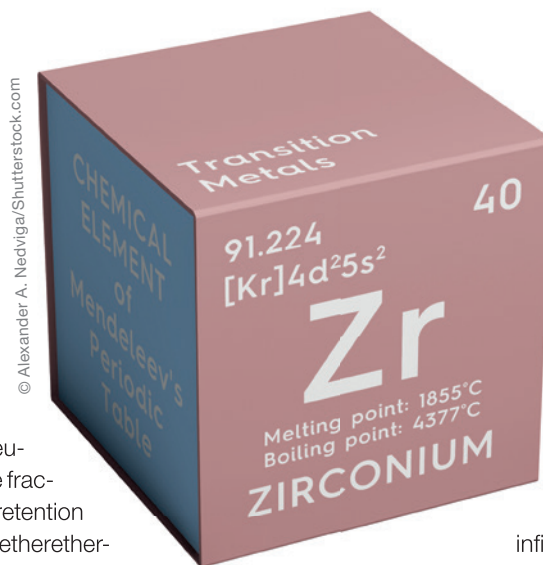
Additionally, a study by Neumann et al. (2014) compared the fracture resistance of abutment retention screws made of titanium, polyetheretherketone (PEEK) and 30 per cent carbon fibre-reinforced PEEK, using an external hexagonal implant/UCLA-type abutment interface assembly.²³ UCLA-type abutments were fixed to implants using titanium screws (group 1), polyetheretherketone screws (group 2), and 30 per cent carbon fibre-reinforced PEEK screws. They found that the titanium screws had higher fracture resistance, compared with PEEK and 30 per cent carbon fibre-reinforced PEEK screws.

Screwing abutments can be the trend, but cementation on the other hand could be a simpler and less time-consuming procedure as it is also shown in the study by Brüll et al. (2014).²⁴ It is closer to the dentist's basic education, resembles the procedure of cementing a post in natural endodontically treated teeth and requires no extra instruments. A combination of both screwing and cementing though, could make the procedure more complicated. More studies are required to determine the proper abutment material, cementation method and procedure. The restoration materials that will be used together with their limitations should be studied.

Mostly fixed prosthetics on single crowns or small bridges have been presented. The fracture resistance of two-piece zirconia and titanium implant prototypes under forces representative of a period of five years of clinical loading was tested, during an *in vitro* experiment by Kohal et al. (2009).²⁵ In this experiment the crown materials had no influence on the fracture strength of the zirconia implants. Still, in certain cases such as treating a patient with parafunctional chewing, a softer prosthetic material could be a wise choice. The need for further investigation on removable prosthetics on zirconia implants should be kept in mind, too.

Peri-implantitis

Peri-implantitis in titanium implants is a serious and underestimated problem involving millions of implants. The prevalence of peri-implantitis according to the review of Zitzmann and Berglund (2008) varies between 12 and 43 per cent of implant sites.²⁶ Many aetiological factors have been implicated, bacterial contamination among them. In peri-implantitis, the lesion extended



apical to the pocket epithelium contains large proportions of plasma cells and lymphocytes but also PMN cells and macrophages in high numbers.^{27,28} Peri-implantitis though has hardly been reported on zirconia implants. Zirconia demonstrates a low affinity to bacterial plaque, small amounts of inflammatory

infiltrate and good soft tissue integration. These properties might lower the risk for peri-implant diseases.¹⁻³ This hypothesis is strengthened by the results of the study conducted by Nascimento et al. (2014), where cast and polished titanium were presented with the highest incidence and total count of bacteria, while zirconia showed the lowest.²⁹

Rosenberg et al. (1991) claimed distinct differences between bacterial profiles of infected and overloaded titanium implants.³⁰ The latter were characterised by the absence of motile rods, spirochetes and classical periodontopathogens, along with a predominance of Gram-positive organisms, similar to what is observed in periodontal health. These observations were supported by Quirynen and Listgarten in 1990.³¹ Failures of zirconia implants due to bacteria, should be differentiated against those of technical reasons and the microbiota should be investigated. It should be kept in mind that bacterial cells have a net negative charge on the cell wall, although the magnitude of this charge varies from strain to strain. Especially on the Gram-negative bacteria, LPS as a major component of their cell membrane increases even more the negative charge.³²

Titanium is also negatively charged, thus acting repulsively to bacteria. This could be one of the reasons of success of titanium implantation in a contaminated environment. Zirconia though has no electric charge. Depending on the roughness and the hydrophilic surface of every zirconia implant system, contamination may be easier to occur and this could be a reason of early failure when zirconia is implanted in a contaminated environment. Studies are needed to clarify whether the latter could affect the osseointegration result and what is the relative danger comparing to titanium. Local disinfection could minimise the risk in immediate implantation using the help of ozone and autologous plasma. Nutrition and food supplements could also be helpful, too.

Intolerance to titanium and genetic predisposition to inflammation has been introduced as an additional and independent risk factor (Odds Ratio 12 and Odds Ratio 6 respectively) for peri-implantitis.³³ The authors propose a direct effect of the released microparticles of titanium on the immunological mechanism of the body that could possibly initiate peri-implantitis. Zirconia particles on the



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Microparticles released by titanium on the immunological mechanism of the body could possibly initiate peri-implantitis. Pictured: Titanium-infused quartz crystal cluster.

other hand have no effect on the release of $TNF-\alpha$.³⁴ Titanium microparticles are released as a result either of friction, electrochemical corrosion, or the synergistic effect of both and can either be taken up by macrophages, remain in the intercellular space near the releasing site, or systemically migrate in organs such as liver, spleen and lung, as Olmedo et al. (2003 and 2002) found.^{35,36}

Same group of authors made a long-term evaluation of the distribution, destination, and potential risk of both TiO_2 and ZrO_2 microparticles, in an animal study.³⁷ They evaluated:

- (a) the presence of particles in blood cells and liver and lung tissue,
- (b) Ti and Zr deposit quantitation,
- (c) oxidant-antioxidant balance in tissues, and
- (d) O_2^- generation in alveolar macrophages.

Ti and Zr particles were detected in blood mononuclear cells and in organ parenchyma. At equal doses and times post administration, Ti content in organs was consistently higher than Zr content. Ti elicited a significant increase in O_2^- generation in the lung compared to Zr. The consumption of antioxidant enzymes was greater in the Ti than in the Zr group.

Conclusion

Scientific studies are promptly needed to fulfil gaps like long-term clinical evaluations of all existing zirconia implant systems. Protocols used to design, manufacture and test titanium implants cannot simply apply to produce and evaluate the zirconia ones. Every step, from production to surgery and prosthetic reconstruction needs to be carefully planned, with respect to the properties of the new material. Accordingly, the advantages of zirconia would be fully beneficial and the risk of failure could be minimised.



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