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Zirconia Materials for Dental Implants: A Literature Review

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Titanium is currently the most commonly used material for manufacturing dental implants. However, its potential toxic effects and the gray color have resulted in increasing requests for metal-free treatment options. Zirconia is a type of ceramic materials that has been extensively used in medicine field, such as implant abutments and various joint replacement appliances. Amounts of clinical evaluations have indicated good biocompatibility for zirconia products. Besides, its toothlike color, low affinity for plaque and outstanding mechanical and chemical properties have made it an ideal candidate for dental implants. The aim of this study is to review the laboratory and clinical papers about several kinds of zirconia materials and zirconia surface modification techniques. Although there are plenty of literatures on these topics, most of the researches focused on the mechanical properties of the materials or based on cell and animal experiments. Randomized clinical trials on zirconia materials are still urgently needed to validate their application as dental implants.

Keywords: zirconia, implants, surface modification, biocompatibility, mechanical properties

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INTRODUCTION

Over the past few decades, dental implant procedures were applied to support single crowns as well as fixed or removable partial or full dentures. Early osseointegration is a critical factor for the clinical success of oral implants. Titanium showed a high biocompatibility, resistance to corrosion and favorable mechanical properties, these characteristics were particularly relevant in the early osseointegration of the healing period. Nevertheless, failures of titanium implants were hard to avoid. To improve titanium surfaces, several methods have been used, one of these methods was to deposit a coating on the surface of titanium.

Zirconia was first introduced to implant dentistry in the form of coatings to improve osseointegration of the titanium implants (1). As people moved toward further exploration, the unique characteristics of zirconia such as superior toughness, strength, fatigue resistance and corrosion resistance made it an ideal implant material (2). Besides, clinicians and patients started to reconsider about the safety of titanium implants after the accumulation of titanium particles was detected in tissues close to the implants and local lymph nodes (3). Some reported about the allergy caused by the application of titanium implants (4). As of now, there is no report about the toxicity of zirconia implants. Another advantage of zirconia is its tooth-like color. To meet with esthetic needs from patients, the ivory color offers a possibility of staining zirconia with tooth or gingival colors, which elevates the esthetic scores and leads to patient satisfactions (5).

The successful use of zirconia as a material for dental implants is mainly contributed by its excellent osseointegration behavior. According to the *in vivo* studies, zirconia has shown predictable osseointegration, cell metabolism and positive tissue response, some results were taken out under loaded conditions (6, 7). Furthermore, the inflammatory response and bone loss induced by zirconia implants are much less than those induced by titanium implants, suggesting the good biocompatibility of zirconia material (8–11). In the quest to achieve more predictable osseointegration, especially in difficult clinical sites, researchers have attempted to modify zirconia surface to make it desirable for a better cell attachment, growth, proliferation and differentiation. The methods on improving zirconia surfaces were reported as preclinical results, most of the surface modification procedures promoted a superior cell response. The purpose of this study is to perform a literature review on different kinds of zirconia for dental implants and surface modification techniques of zirconia implants, analyze their behavior via preclinical evaluations and clinical trials.

MATERIALS SELECTION AND CHARACTERISTICS

Zirconia

When people started to explore whether ceramic implants are alternative to titanium implants, alumina implants were shortly used as an implant material. But clinical investigations using different alumina oral implants showed poor survival rates for different indications (12). Thereafter, biomedical grade zirconia was introduced to solve the problem caused by the fracture or potential failure of alumina implants (13). One of the advantages of zirconia is that the phase transformation inside the material increases its crack propagation resistance. However, the metastability character of zirconia also causes its aging in the presence of water (14). The consequences of aging did not cause manufacturers' attention until the year 2001, 400 femoral heads made of zirconia failed in a very short period (15). After that, researchers expended considerable efforts seeking to resolve this problem. One of the approaches was to add oxides to stabilize the crystal structure transformation during firing at an elevated temperature and improve the physical properties of zirconia.

As mentioned above, zirconia can undergo a phase transformation at different temperatures. Upon heating, the monoclinic phase of zirconia starts transforming to the tetragonal phase. On cooling, the transformation is from the tetragonal to the monoclinic phase. A disadvantage of the phase transformation is that during the transformation, there is a 4% volume change, which results in the formation of ceramic cracks. It is known that the phase transformation can be induced by stress, heat and high energy heavy ion irradiation, but the mechanism is not clear yet (16–22). Oxides such as ceria, yttria, alumina, magnesia and calcia have been used to stabilize the structure of zirconia when calcination temperatures changes. The mechanism of the stabilization is to stop tetragonal phases from transforming into monoclinic phase under normal cooling conditions, and consequently, crack formation, due to volume changes, is avoided (2). In this review, Y-TZP (Yttria-stabilized Tetragonal Zirconia Polycrystal ceramics) and NANOZR (ceria-stabilized zirconia/alumina nanocomposite) are included for their wide application as dental implant materials.

Yttria-Stabilized Tetragonal Zirconia Polycrystal Ceramics

Currently the material most often chosen for ceramic dental implants is Y-TZP. Y-TZP has a clear benefit to the aging resistance, as well as preserving good toughness and strength. Y-TZP retains some promising physical and mechanical properties, including low thermal conductivity, high flexural strength (900–1,200 MPa), favorable fracture resistance, as well as wear and corrosion resistance. Besides, an advantage of the phase transformation is that due to the unit cell of monoclinic configuration occupies about 4% more volume than the tetragonal configuration, the volume increase essentially squeezes the crack to close and thus increases its toughness. The surface toughening further improves the properties of Y-TZP (23). As a kind of implant material, clinicians always pay close attentions on its resistance to fracture. In Silva's research (24), titanium implant with titanium abutment, titanium implant with zirconia abutment and one-piece zirconia implant were tested to determine their fracture resistance to impact load. The result of their experiment was that the fracture energy for all three test groups was not statistically significant, ranging from 3.2 to 5 J. The results are nearly three times higher than the energy needed to fracture the most resistant natural teeth (maxillary cuspids), which was reported ∼1.26 J. Therefore, we can assume that a patient receiving a traumatic injury would result in fracture of a natural tooth, but not fracture of a zirconia implant or abutment.

However, a negative property of zirconia, which is described as low-temperature degradation (LTD) or aging, results in large decreases in strength, toughness and density. The LTD can be summarized as a slow transformation from the tetragonal phase into the monoclinic phase. The phase transformation is greatly enhanced by the presence of water or water vapor and accompanied by micro- and macrocracking, which leads to progressive deterioration of the material (25). Nowadays, several studies have been performed on the LTD phenomenon, but these are still in need of further investigations.

NANOZR (Ceria-Stabilized Zirconia/Alumina Nanocomposite)

To avoid the low-temperature degradation, a ceria-stabilized zirconia/alumina nanocomposite (NANOZR) was introduced to dentistry. NANOZR is highly resistant to low-temperature degradation and therefore suitable for load-bearing applications such as dental implants. It also exhibits greater flexural strength and fracture toughness when comperes with Y-TZP (26). According to some studies, NANOZR is a good candidate implant material because of its good osseointegration capacity (27, 28).

SURFACE MODIFICATION TECHNIQUES

Polishing

Polishing is to use silicon carbide polishing paper and diamond suspension with a polishing machine. The procedure usually results in a very smooth surface even observed using a microscope. It is known that epithelial cells are more likely to attach to a smooth polished surface than to a rough surface, and a smooth surface is a favorable circumstance for epithelial cell proliferation (29). Oral keratinocyte is a kind of highly specialized epithelial cell. According to Kimura's study, when detecting the responses of keratinocytes to an implant material, a polishing surface of zirconia made it comparable to titanium (30).

Sandblasting and Acid Etching

Sandblasting and acid etching are most common procedures using for implant surface modification. One of the advantages is that this treatment process can increase the surface area of implants for osseointegration (31). Another is that rougher surfaces have been proved to enhance osteoblast adhesion and proliferation (32). For zirconia implants, according to related reports, the RTQ (removal torque) value was significantly more for sandblasted zirconia than machined zirconia (33). Besides, the corporation of fluoride at zirconia surface could enhance osteoblastic differentiation and interfacial bone formation. It was reported that BIC of HF etched zirconia is approximately 81% (34).

There are also some disadvantages of sandblasting. Studies showed that the sandblasting process can cause deep micro-cracks, which may result in the reduction of strength (31). Therefore, a proper protocol is needed when treating zirconia surface with sandblasting to avoid the decrease of the strength.

Ultraviolet Light Treatment

UV treatment is an effective physicochemical method for surface modification of zirconia implants. UV light can induce electron excitation, increase zirconia surface energy, and result in a super-hydrophilic surface (35). Hydrophilicity is one of the key factors for enhancing the attachment, growth, proliferation, and differentiation of osteoblast (36). One *in vivo* study showed that the super hydrophilic surface of zirconia increased osteoblasts attachment and spreading, and then induced faster healing and higher BIC percentage (37). Besides, in Att's study, the atomic percentage of hydrocarbon changed after UV treatment, which resulted in a better protein adsorption and cell adhesion (38). In conclusion, UV surface treatment is a promising strategy to promote bone morphogenesis around zirconia implants.

Laser Treatment

Many studies have reported using laser treatment to modify the surface properties of zirconia. The main mechanism for laser to improve the surface is that the treatment increases the surface energy and consequent wettability (39), which plays a key role in protein adsorption and cell adhesion. Another advantage of laser treatment compared to other surface treatment methods is that it can produce microscale patterns with regular geometry instead of random surface patterns. The laser-induced periodic surface structures have been proved to improve osseointegration, reduce biofilm formation, and enhance soft tissue attachment (40). Besides, significantly higher BIC and RTQ is related to a laser-treated zirconia implant (41, 42). However, the laser treatment induces thermal cracking, which can reduce mechanical strength. The laser also induces phase transformation of zirconia, which may impair the long-term stability of dental implants. Therefore, the choice of laser treatment process and the consequential microcrack should be taken into consideration (40).

Self-Assembly

Self-assembly is defined as the autonomous process by which components organize into patterns or structures without external intervention (43). In the year 2008, Rauscher found a pseudo periodic-array of nano islands on the surface of YZP after thermal treatment (44). This nanostructure was further investigated, and reported to have satisfying cellular responses such as better cell spreading and cytoskeletal protein distribution (45).

Coatings

Different coatings on zirconia surfaces have frequently been applied to improve surface properties. Among the many kinds of coatings, Hydroxyapatite (HA) is an important one that explored deeply by many researches. HA has a similar mineral composition to that of bone, and thus shows bioactive properties that enhances osseointegration (46). Calcium phosphate (CP) is another bioactive coating with a chemical composition close to that of the mineral phase of bone. CP-based material allows zirconia implant to form a rigid bond with surrounding tissue, and results in good performance in early-osseointegration (47). However, both HA and CP coatings were reported with poor stability and weak bonding strength. To overcome these drawbacks, some filler materials, i.e., tricalcium phosphate and zirconia powder, were added into the coatings to enhance the coatings' strength (48, 49). Not only to convert the inert zirconia into a bioactive material, some coatings also act as drug delivery systems (50). Porous zirconia scaffolds coated with HA have been used as a drug delivery system to enhance bone response and assure proper osseointegration (51). In summary, bioactive coatings can enhance the biocompatibility and osteogenic response of zirconia, but most of the reports are preclinical studies, clinical trails are still needed.

PRECLINICAL AND CLINICAL EVALUATIONS

Bone-to-Implant Contact

BIC is commonly measured by histomorphometric analyses at different time points and used to assess the quality of osseointegration in a quantitative manner. According to current studies, tibia of rabbits (6), tibia of minipigs (52), jaws and femur of sheep (53), mandible of dogs (54), and maxilla of monkeys (55) have been used to investigate the BIC of zirconia. Both functionally loaded or not loaded implants were included. Titanium implants were most used as a control group to compare with zirconia implants. These studies proved that both titanium and zirconia surfaces were osteoconductive, and most of the studies reported that the two materials did not have any significant different effect on the BIC values (56–58), while some reported that zirconia was better (59, 60). Yet BIC values depend a lot on the individual animal model, the difference was significant (56). Compared to unloaded and immediately loaded implants, conventionally loaded implants showed significantly increased BIC values (61, 62). For different study durations, people founded that a longer investigation and loading period could result in a significant increase in BIC values (63, 64). In summary, all of the studies demonstrated excellent BIC values around zirconia implants, although the values may vary depending on the study animals and the loading status.

Removal Torque

RTQ is a quantitative way for assessing osseointegration via calculating the torsional strengths needed to remove an inserted implant. The effect of different implant materials on RTQ is controversial. According to current studies, some reported no significant differences in RTQ between zirconia and titanium (58, 63, 65), while some reported that RTQ was significantly lower for zirconia implants than for titanium implants (66–69). However, RTQ is depending a lot on different surface modifications. Some authors reported that zirconia implants with decreased surface roughness could reach equivalent RTQ values compared to control titanium implants with increased surface roughness (70). In one study, researchers compared the biomechanical properties of six types implant surfaces and found that the RTQ values were highest for the SLA titanium, followed by SLA and Calcium phosphate (CaP)-coated titanium, SLA and bisphosphonate-coated titanium, SLA and collagen-coated titanium, SLA zirconia and SLA and anodic plasma chemical surface-treated titanium (66). However, when modified titanium implants were compared with modified zirconia implants, the RTQ values were similar (71). These results can be summarized that RTQ depends more on different surfaces than different materials. Some other factors also may have an impact on the RTQ values. According to some reports, a longer loading period is always related to a significantly increase in RTQ (60, 72). Besides, conventionally loaded implants showed increased RTQ compared to unloaded implants (56). A meta-analysis upon preclinical evaluations using different animal models revealed that the individual animal model also significantly influenced the evaluated RTQ outcomes (56).

Push-In

Push-in test in combination with histomorphometry was first established by Ogawa, using as a valid model for research of the osseointegration process in an established rat-animal model (73). The main impact factors on PI values include surface topography, individual animal model and PI testing protocols. Kohal compared two kinds of materials, titanium and zirconia, with different surfaces. It turned out that there was no significant difference between the modified titanium surface and the modified zirconia surface, while the values were significantly higher compared with the machined implant surfaces. Moreover, the study also reported that significantly decreased PI values for zirconia compared to titanium were associated with an increased surface roughness value (63). These can be summarized that PI differences between titanium and zirconia are related to surface topography characteristics and not to material properties.

Survival Rate

In recent years, zirconia implants have been recommended for excellent esthetic efforts, especially in the anterior maxillary zone. But up to date, there are only a few primary studies about clinical outcomes of zirconia implants, not to mention long-term follow-ups. In spite of the disadvantages of titanium implants such as potential local and systematic toxicity and gray color, the long-term clinical survival rate has been proved sufficiently. Data from recent systematic reviews suggest that the survival rate of titanium implants that support single crowns is ∼97.2 and 95.2% over a period of 5 and 10 years, respectively (74). These results are relatively ideal for the clinical application of an implant material. However, some clinicians still consider that zirconia implants may not offer a sufficient validation of their performance as equivalent to or better than titanium implants.

According to Elnayef's meta-analysis (75), the survival rate of 1,948 zirconia implants is 91.5%, significantly lower than that of titanium implants. Thus, he concluded that for certain conditions, such as a thin gingiva or in the maxillary anterior area, zirconia implants may offer some benefit. In another study, Pieralli reported a 1-year implant survival rate of 95.6%. They also mentioned that most of the implant failures occurred in the early healing period, followed by a survival rate decrease of 0.05% per year (76). Other studies reported the survival rate after 12 months ranged between 85% (77) and 100% (78, 79). It can be inferred that the differences among the outcomes of clinical trials may be related to the insufficient duration for investigations and the shortage of long-term studies.

Marginal Bone Loss

Several prospective clinical trials evaluating MBL as a secondary outcome have been performed since 2010 (76). As the same as the survival rate, there are great differences among the reports. As a quantitative index, MBL was reported ranging from 0.7 mm (56) to 0.98 mm (80). In some studies, zirconia implants were reported as presenting similar MBL outcomes to titanium implants (76, 81). However, according to Elnayef's research, titanium implants performed better than zirconia implants upon the comparison with MBL (75). While in Vohra's research, the results were opposite (82). In conclusion, the short-term clinical outcomes of zirconia implants are acceptable, but evaluation of long-term outcomes are still needed to compare the clinical performances between zirconia implants and titanium implants.

CONCLUSIONS

The present review analyzed the zirconia implant materials currently used and the techniques reported for zirconia surface modifications. In summary, zirconia is a good candidate for dental implant because of its good mechanical, esthetic and biocompatible performance. Zirconia dental implants have deeply been studied and promising results in clinical trials have been shown. Considering outcomes of preclinical studies and clinical trials are sometimes controversial when compared with titanium, whether zirconia material will be used as an alternative to titanium is not clear due to the lack of long-term follow-ups. Surface modifications of zirconia implants were investigated widely, most of the modification methods are proved beneficial to zirconia implants in several aspects, including enhancing cell response and improving their osseointegration. But the investigations are not as sufficient as those of titanium implants. For most of the techniques, clinical trials are still needed.

AUTHOR CONTRIBUTIONS

YQ was in charge of manuscript preparation. LL contributed to literature research and manuscript revision. All authors contributed to the article and approved the submitted version.

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