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Review Article

The Role of Zirconia Implants in Implantology: Potential Benefits and Challenges

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Abstract

Background: The search for an alternative to titanium dental implants has been ongoing for over 50 years. While titanium implants have significantly improved patients' quality of life, concerns about titanium sensitivity and corrosion have prompted interest in ceramic implants. Zirconia, in particular, offers biocompatibility and aesthetic benefits, especially for patients with thin gingival biotypes or those prone to gingival recession. *Objective:* This review aims to summarize the current knowledge on the use of zirconia ceramics in dental implant prosthodontics and assess its potential to replace titanium while maintaining high success rates. *Methods:* A review of the literature was conducted, focusing on zirconia implants, including one-piece and two-piece designs, covering mechanical properties, osseointegration, clinical outcomes, and challenges. *Results:* Zirconia implants show promising advantages, such as reduced sensitivity, minimal ion release, and improved aesthetics, particularly in patients concerned with the cosmetic outcomes of titanium implants. However, challenges remain, including mechanical fragility, surface treatment needs, and the risk of early failure. Despite these challenges, advancements in zirconia implant design and surface modifications have led to improved clinical outcomes, though zirconia implants have not yet reached the routine use of titanium implants. *Conclusions:* Zirconia implants present potential as a non-metallic alternative to titanium. However, their clinical use is still evolving, and further research and development are needed to ensure their long-term success and mechanical performance.

Keywords

Biocompatibility, Osseointegration, Zirconia Implants, Implant Design, Ceramic Dental Implants

1. Introduction

Ceramic materials, particularly zirconia bioceramics, have emerged as transformative substitutes for traditional materials across various industries, including medicine. Continuing the tradition of defining historical periods by the predominant materials of the era, the modern age can aptly be termed the "ceramic age" due to the widespread application and advancements in ceramic technology [1-3].

The history of ceramics dates back to as early as 28,000 BCE, during the late Paleolithic period. Among the earliest artefacts is a statuette discovered in a prehistoric settlement in the Czech Republic. Ceramics facilitated the development of tools, water transport, and decorative utensils. Around 5,000 BCE, through the constant firing of clay, early glass-like materials were created. The Chinese civilization pioneered the

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manipulation of clay and sand at temperatures reaching 1,350 ℃, leading to the creation of porcelain, characterized by less than 1% porosity [4-8].

From the 16th century onward, ceramics underwent significant transformation. These materials became ubiquitous, and innovations exploited their unique properties, including low thermal and electrical conductivity, high chemical resistance, and a high melting point [7, 9, 10]. Today, ceramics are integral to technologically advanced fields such as electronics, energy, aerospace, and medicine. Their exceptional properties have also enabled the development of dental materials suitable for oral rehabilitation [3, 6, 11].

The use of ceramics in dentistry can be traced back to the 18th century. Pierre Fauchard, in his seminal book Le Chirurgien Dentiste, highlighted porcelain's potential to mimic the appearance of natural teeth [12]. This innovation supplanted the practice of using extracted human teeth and animal materials, paving the way for “mineral teeth” in restorative dentistry [13, 14].

In the 1960s, research on ceramics expanded significantly, exploring their applications not only as aesthetic dental materials but also as biomaterials for bone replacement [5, 15, 16]. The first study on the in vivo biocompatibility of zirconia ceramics (ZrO_2) was published in 1969 by Halmer and Driskell [11, 17, 18]. This research, along with further studies into zirconia and alumina ceramics, has advanced knowledge and technologies that serve dental and oral rehabilitation [19].

This review aims to summarize the current data on the use of zirconia ceramics in implant prosthodontics, focusing on their material properties, clinical applications, and the challenges associated with their use.

2. Materials and Methods

A comprehensive literature search was conducted using the databases OVID, PubMed, Google Scholar, Scopus, and the University of Sydney’s scientific articles repository. The search was limited to studies published in English between 1980 and 2022. The following keywords were used in combination: *"ceramic," "zirconia," "dental implants," and "dental implant biomaterials."*

After screening the abstracts for relevance, 45 articles were selected for inclusion in this review. These articles specifically addressed the role of zirconia ceramics in dental implants and their importance in clinical practice. Additional articles that provided foundational knowledge or context were also incorporated to support the narrative and discussion.

3. Background

The 1960s and 1970s marked a pivotal era in dentistry, characterized by a surge in dental implant innovation. During this period, various materials and implant designs were explored to restore missing dentition. However, early metallic implants faced several limitations, prompting the need for alternative materials. The first significant attempt to replace metals in dental implants was the Tübingen implant, introduced in 1974 by Professor Schulte and colleagues [20]. These alumina-based implants demonstrated excellent biocompatibility and favourable plaque adhesion properties. However, they were plagued by frequent fractures and poor survival rates, which ultimately led to their discontinuation in the market [20-23] Figure 1.

The shortcomings of alumina implants spurred further research into new implant designs and materials. By the early 2000s, concerns surrounding titanium implants, including reports of corrosion and potential systemic effects, further fuelled the search for alternatives [24-28]. This momentum led to the introduction of zirconia implants. In 2006, Volz and colleagues reported the outcomes of a 2- to 5-year follow-up study involving 66 zirconia implants (Z-systems) placed in 34 patients. The results demonstrated that 97.5% of the implants achieved successful osseointegration and exhibited favourable soft tissue reactions. Additionally, the zirconia implant surface was noted to have lower plaque affinity than titanium, facilitating improved oral hygiene. These characteristics made zirconia implants particularly suitable for patients with high aesthetic demands or metal allergies [29].

Figure 1. *Horizontal fracture of an alumina ceramic implant tooth 12, in service for 30 years. [30].*

4. Characteristics of Zirconia Implants

The use of zirconia as a ceramic biomaterial in dental implant applications has seen significant growth due to its promising properties. Zirconia exists in three crystalline phases: monoclinic, cubic, and tetragonal. Of these, the tetragonal phase is the most commonly used in clinical applications. To enhance its stability and resistance to aging, yttrium is added to zirconia, resulting in Yttria-Stabilized Tetragonal Zirconia Polycrystal (YTZP) [31]. This bioinert material is six times harder than stainless steel, making it an attractive alternative to titanium in implant dentistry.

Zirconia exhibits several characteristics that make it an ideal candidate for use in dental implants, including:

Electrical neutrality: Zirconia is electrically neutral, reducing the potential for electrical interactions with surrounding tissues.

Low thermal conductivity: Its low conductivity helps protect the surrounding tissues from thermal damage during implant placement.

High heat resistance: Zirconia can withstand high temperatures without significant degradation, making it a robust material for implant applications.

Thermal shock resistance: The material's ability to resist cracking or failure due to rapid temperature changes is particularly valuable in clinical settings.

Chemical stability: Zirconia remains chemically stable in the presence of bodily fluids, making it highly durable in the oral environment.

Aesthetic similarity to tooth structure: Zirconia's color closely resembles that of natural teeth, which makes it an excellent choice for implants, especially in the aesthetic zones.

Mechanical strength and fracture toughness: Zirconia has superior mechanical properties, offering high strength and resistance to fractures, which is essential for implant durability.

Biocompatibility: Zirconia has excellent biocompatibility, with minimal adverse tissue reactions. It is well-tolerated by the body and promotes favourable tissue integration.

Low ion release: Compared to metallic implants, zirconia releases significantly fewer ions into the body, reducing the potential for systemic effects.

Enhanced bone integration: The microstructure of zirconia provides nucleation sites for the development of calcium-based minerals, facilitating better bone integration and osseointegration [31-33].

Although titanium implants have been the gold standard in dental implantology for over 50 years, they present certain aesthetic challenges. Specifically, the dark color of titanium implants can become visible through the gingiva in cases of gingival recession or when the patient has a thin biotype. In contrast, zirconia's white color provides a distinct advantage in such cases, as it mimics the natural appearance of teeth and improves both white (implant) and pink (gingiva) aesthetic scores [34-36].

Additionally, zirconia implants have been associated with a favourable immune response. They exhibit minimal immune reactions, which is particularly beneficial for patients who suffer from hypersensitivity to titanium implants [37-39]. However, while the interaction between zirconia and soft tissues is an area of active investigation, evidence regarding the soft tissue integration of zirconia implants remains inconclusive [38, 40, 41]. Research has shown that surface treatments such as acid-etching, oxygen plasma treatment, ultraviolet irradiation, sandblasting, laser treatment, bioactive ceramic coatings, and the incorporation of peptides can improve the affinity of soft tissues to zirconia, potentially enhancing the success rate of soft tissue integration [42-46].

The mechanical strength of zirconia implants (particularly one-piece designs) ranges from 725 to 850 N, which is comparable to, or in some cases, higher than certain titanium alloys [47]. Despite these promising mechanical characteristics, the long-term survival rates of zirconia implants are generally reported to be slightly lower than those of titanium implants. The survival rates of zirconia implants range from 79.3% to 92%, while titanium implants exhibit survival rates of 95% to 97% [48]. Common causes of failure for zirconia implants include early implant loss, fracture, and excessive bone loss. Interestingly, surface treatments have been shown to help reduce bone loss and improve implant stability [19, 43, 48, 49].

Despite its many strengths, zirconia remains a brittle material, and fractures can occur during the insertion process or as a result of excessive mechanical stress. Adherence to the manufacturer's instructions during the placement procedure is critical to avoid catastrophic failures [50]. Additionally, as zirconia is more brittle than titanium, careful consideration of the implant design, as well as the insertion protocol, is necessary to minimize the risk of fractures.

Zirconia implants offer a range of benefits, including superior aesthetics, biocompatibility, and mechanical strength. However, challenges such as soft tissue integration, fracture risk, and long-term survival rates still need to be addressed. Ongoing advancements in surface treatments, implant design, and clinical techniques are likely to improve the long-term outcomes and broader adoption of zirconia implants in dental practice.

4.1. Osseointegration of Zirconia Oral Implants

Zirconia has gained widespread use in medicine due to its excellent osteoconductive properties, which facilitate osseointegration. These properties have made zirconia a promising material for dental implants. The osseointegration process of ceramic implants has been well-documented in the literature [51, 52]. Following the initial surgical placement of zirconia implants, necrotic bone spots may be evident around the implant site, but these areas are typically resorbed within the first four days. By the end of the first week, the implant surface begins to interact with the surrounding tissues, and a fibrinous and collagenous matrix starts to form, creating contact with the porous surface of the zirconia implant. After approximately 16 days, the implant surface is covered by a mixture of mineralized tissue, osteoid, and a dense extracellular matrix. After 12 weeks, mature bone is found in intimate contact with the surface of the zirconia implant [51, 53-55].

This sequence of healing events is similar to that observed with titanium implants, and no significant differences in the osseointegration process have been identified between zirconia and titanium implants [39, 51]. In a study by Depprich et al. (2008), the osseointegration of zirconia implants was compared to that of titanium implants in an in vivo animal model using minipigs. The study found that zirconia implants with modified surfaces demonstrated similar osseointegration properties to titanium implants [56]. These findings have been corroborated in other animal studies, which compared the removal torque of zirconia and titanium implants, showing mixed results in terms of osseointegration [51, 57-60].

The success of osseointegration in both zirconia and titanium implants appears to be closely linked to the surface treatment of the implant. Surface modifications play a crucial role in enhancing the bonding between the implant and bone tissue, and both materials benefit from such treatments. However, the specific surface treatments required for zirconia implants to achieve optimal osseointegration are still a subject of ongoing research.

An unusual event that has been reported in the osseointegration process of zirconia implants is the unexpected loosening of the implant between 3 to 10 months after placement. This event, described as a sudden failure of osseointegration, has been likened to aseptic loosening in hip replacements [61]. While this occurrence has been rare, it highlights the importance of monitoring long-term implant stability and suggests that further investigation into the underlying causes of this phenomenon is necessary.

Zirconia implants exhibit favourable osseointegration properties, with healing processes that are comparable to those of titanium implants. Surface treatments are critical for optimizing osseointegration, and while overall outcomes have been positive, further research is needed to explore the causes of rare occurrences of implant loosening and to refine the methods for improving long-term implant stability.

4.2. Zirconia Dental Implant Systems

Zirconia dental implants have been in clinical use for several years, with various surface treatments, shapes, and components available. Over time, numerous companies have invested in the development and commercialization of ceramic implants. Some of these companies, such as Zeramex, Z-Systems, SDS, Straumann, Ceraroot, Nobel Biocare, Bredent, Axis, Moje KI, Vita, Relmplant, Konus, Sigma, Goei, and Ziterion, have been pioneers in the field, with over 20 years of experience using these types of implants [43, 62, 63]. Initially, these ceramic implants were fabricated as one-piece designs, but due to challenges related to restoration, newer two-piece designs have been introduced to the market. Figure 2.

Figure 2. *Ceramic Implants by Z-SYSTEMS^{TM}.*

4.3. One-Piece Zirconia Implants

The original one-piece design of zirconia implants was intended to maintain the strength of the material by avoiding hollowing out the implant body. This design was initially considered advantageous, as it preserved the integrity of the zirconia implant, but it came with several limitations and required high technique sensitivity [64].

Surgical placement of one-piece zirconia implants demands precise planning to meet both the bony and prosthetic requirements of the patient. Misalignment is particularly problematic, as it cannot be corrected post-placement, and grinding the abutment is contraindicated. Modifying the abutment in any way could compromise the fracture strength of the implant, as it would expose the one-piece component to the forces of mastication or the tongue, which could lead to early failure (39). Furthermore, rehabilitation with one-piece zirconia implants is typically limited to cement-retained prostheses, which carry the risk of excess cement accumulation, as noted in the literature [65-67].

In a longitudinal study by Spies et al. (2019), 45 patients who received single crown restorations on zirconia implants were followed for five years. The study, which aimed to evaluate restoration outcomes, reported only one implant failure, resulting in a survival rate of 97.8% [68]. Similarly, Borgonovo et al. (2013) assessed the survival, success rates, soft tissue health, and radiographic marginal bone loss of zirconia implants placed in both aesthetic and posterior areas of the jaws. The study involved 28 implants—20 in the maxilla and 8 in the mandible—and found a minimal reduction of crestal bone (1.5 mm) after five years of follow-up. The authors attributed this minimal bone loss to the absence of a micro-gap between the fixture and abutment, which resulted in fewer bacterial accumulations on the ceramic surface. However, the literature generally reports early failures with one-piece zirconia implants, particularly due to exposure to early masticatory forces and tongue pressure, which can lead to complications [69].

The main challenges associated with one-piece zirconia implants lie in their inherent design limitations. The inability to adjust or realign the implant after placement, along with the sensitivity of the material to masticatory forces, increases the risk of early failure. Although the survival rate in some studies remains promising, the general consensus indicates that the one-piece design may not be as adaptable or durable in the long term, particularly in patients with high functional demands or those with parafunctional habits.

As a result, many implant systems have evolved to incorporate two-piece designs, which provide greater flexibility in terms of restoration and adjustments, leading to better outcomes for patients requiring implant rehabilitation.

4.4. Two-Piece Zirconia Implants

In response to the limitations of one-piece zirconia implants, efforts have been made to develop two-piece zirconia implants. These implants are particularly useful in situations where primary stability cannot be achieved, bone augmentation procedures are required, or optimal implant positioning is not possible. One of the primary advantages of a two-piece implant design is that it minimizes the transmission of unwanted forces to the healing bone. Additionally, a submerged implant design reduces the risk of infection by preventing direct exposure to the oral microbial environment, facilitating a more stable osseointegration process.

However, the two-piece design introduces new challenges, notably the increased fracture risk due to the hollow implant body and the connecting screw, which is often considered the weakest link in the system. Various materials have been explored for prosthetic screws, including gold, titanium, PEEK, carbon fibre, and zirconia. Each of these materials has unique properties that may affect the performance and longevity of the implants [70, 71].

While two-piece zirconia implants are still undergoing testing in prosthodontics, several studies have provided valuable insights into their performance. In an in vitro study by Kohal et al. (2009), biomechanical stability at the abutment screw level was found to be borderline for clinical use, suggesting that further developments were needed for these implants to be considered fully reliable [70]. However, a subsequent investigation by the same group (Spies et al., 2016) showed that two-piece zirconia implants were capable of withstanding physiological chewing forces, indicating improved biomechanical performance [71].

A prospective study by Cionca et al. (2015) reported a survival rate of 87% after one year of loading. Although all failures were attributed to aseptic loosening, the study noted that the abutments could be replaced, and the loose implants were removed without complications. No implant fractures were reported during the study period [61].

Prayer et al. (2015) conducted a randomized control trial comparing 16 zirconia implants and 15 titanium implants of similar shape over a two-year period. The results showed no significant differences between the two implant types in terms of performance, further supporting the potential of zirconia implants in clinical practice [72]. Similarly, Stagnell et al. (2019) conducted a pilot study comparing 14 zirconia implants with 14 titanium implants. In this study, two implants were lost in the zirconia group, and one implant was lost in the titanium group; however, none of the failures were due to issues with the implant-abutment connection [73].

Despite the promising results from several studies, the literature remains inconclusive regarding the overall performance of two-piece zirconia implants. Nonetheless, their use in prosthodontics is steadily growing, with more manufacturers investing in their development. The ongoing research and technological advancements in surface treatments and implant designs are likely to improve the clinical outcomes and reliability of two-piece zirconia implants in the future.

5. Discussion

Zirconia ceramic implants have emerged as a potential alternative to traditional titanium implants, particularly for patients seeking non-metallic solutions due to aesthetic or biocompatibility concerns. Over recent years, zirconia implants have garnered increasing attention, with advancements in surface treatments, material science, and implant design contributing to their growing acceptance in dental practice. However, despite these improvements, the evidence supporting their widespread use remains inconclusive. Early studies on zirconia implants highlighted several concerns, including mechanical fragility, difficulty in osseointegration, and challenges with soft tissue integration. These limitations have led to a cautious approach in adopting zirconia implants, despite their promising potential [31, 33].

The biomechanical properties of zirconia implants have gradually improved, with recent studies reporting higher strength and fracture toughness compared to earlier iterations [31, 47]. Zirconia's high resistance to corrosion, its aesthetic advantages, and its ability to support osseointegration make it an appealing choice for certain clinical situations, particularly where aesthetics are paramount. Zirconia's color, which closely resembles natural bone, can address issues with soft tissue aesthetics that are often encountered with titanium implants, especially in patients with thin gingival biotypes or when gingival recession occurs [34-36]. Additionally, zirconia implants exhibit minimal ion release, contributing to reduced adverse biological reactions compared to metallic implants, and a more favourable immune response, particularly for patients with hypersensitivity to titanium [37, 39].

Despite these promising characteristics, several challenges remain. The one-piece zirconia implant design, while beneficial in terms of material strength, presents significant limitations in terms of surgical placement and long-term functionality. The inability to adjust or reposition a one-piece implant after placement makes it technique-sensitive and prone to early failure, particularly in cases where primary stability is not achieved [39, 64]. Furthermore, the inability to manage misalignment or correct the implant position post-placement often results in suboptimal outcomes. The use of a cement-retained prosthesis in one-piece zirconia implants, while a common solution, brings the risk of cement excess, which has been associated with peri-implant complications [65-67].

The introduction of two-piece zirconia implants aims to address some of these limitations. Two-piece designs offer more flexibility in terms of placement, alignment, and restoration, particularly in situations requiring bone augmentation or when primary stability is compromised. This design also reduces the risk of infection by ensuring a submerged implant during the healing phase, protecting the implant from the oral microbial environment [70]. However, two-piece zirconia implants face challenges of their own, notably an increased fracture risk due to the hollow implant body and the connecting screw, which is often considered the weakest component of the system [70, 71]. Several materials, including titanium, gold, PEEK, carbon fibre, and zirconia itself, have been explored for the prosthetic screws, but further research is required to determine the ideal material for long-term success [70].

Early clinical studies of two-piece zirconia implants have shown mixed results. Some studies report favourable outcomes, with survival rates similar to those of titanium implants, while others highlight the occurrence of aseptic loosening and abutment fractures [61, 72, 73]. However, these early failures may be linked to the relatively short follow-up periods and the ongoing refinement of the implant designs. More longitudinal studies are needed to fully understand the long-term stability and success of two-piece zirconia implants. Despite these concerns, the continued development of zirconia implants and the growing body of evidence supporting their use indicate a promising future for these implants, particularly in patients who seek aesthetic and biocompatible alternatives to titanium [31, 33, 39].

Osseointegration of zirconia implants follows a similar sequence of events as titanium implants, with early stages of healing characterized by the formation of a fibrinous matrix, followed by mineralized tissue deposition, and eventual intimate contact between mature bone and the implant surface [51, 53-55]. The ability of zirconia to support osseointegration is well-documented, with studies showing comparable healing patterns to those seen with titanium implants. Nevertheless, variations in the success of osseointegration between different implant systems suggest that surface treatment plays a crucial role in enhancing the biological interaction between zirconia implants and surrounding bone tissue [51, 56].

Despite their advantages, zirconia implants are not without their challenges. One significant disadvantage is the phenomenon of aseptic loosening, a rare but concerning event in which the implant suddenly loses attachment without signs of infection or inflammation [61]. While this issue is not exclusive to zirconia implants and has also been reported in orthopaedic applications, its occurrence in dental zirconia implants raises questions about the long-term stability of the material. Although this issue has been reported infrequently, it remains an area of concern that requires further investigation [39, 61].

The evidence supporting the clinical use of zirconia implants has improved in recent years, with more recent studies showing better outcomes compared to earlier reports [33, 47]. This progress can likely be attributed to the accumulated knowledge in implant dentistry, advancements in surface treatments, and improvements in implant design. As the field continues to evolve, zirconia implants are expected to become a more viable alternative to titanium, particularly for patients who prioritize aesthetics and biocompatibility [31, 33, 39].

6. Conclusion

Zirconia implants, particularly one-piece designs, offer several advantages, such as biocompatibility, aesthetic benefits, and mechanical strength. However, the challenges related to the one-piece design, including difficulties in alignment, restoration, and exposure to early mechanical forces, have led to the development of two-piece zirconia implants. Although long-term studies show promising survival rates for one-piece implants, the overall success of zirconia implants hinges on careful surgical planning, proper placement, and patient-specific considerations. Ongoing advancements in surface treatments and implant designs are expected to further improve the clinical success and reliability of zirconia dental implants.

The evidence supporting zirconia ceramic implants remains inconclusive, but they present a promising alternative as a non-metallic dental implant solution. It is evident, however, that the quality of the available literature has improved over time, with more recent studies yielding better results. This progress can likely be attributed to the extensive body of knowledge accumulated in implant dentistry over the past decade.

One of the main disadvantages of one-piece zirconia implants is the challenge of achieving optimal healing when primary stability is not achieved. This limitation can contribute to a higher failure rate of the implants. Another notable concern is aseptic loosening, a phenomenon reported in both orthopaedic and dental zirconia implants. In these cases, the implant loses attachment during the healing process, without any signs of inflammation or infection, leading to early implant failure.

While zirconia implants hold significant promise, we are still in the early stages of exploring their full potential. The coming years will likely offer further insights and improvements, particularly in the development of more durable two-piece systems and enhanced surface treatments to promote osseointegration and reduce complications. As research continues and clinical experience grows, zirconia implants may become an increasingly important option in the dentist's armamentarium, particularly for those seeking a non-metallic, aesthetically pleasing solution for dental implants.

Abbreviations

YTZP	Yttria-Stabilized Tetragonal Zirconia Polycrystal
BCE	Before Common Era
ZrO_2	Zirconium dioxide

Author Contributions

Andres Felipe Aguirre-Osorio is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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