

Review

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Review

Evaluating the Efficacy, Durability, and Clinical Implications of Zirconia vs. Titanium Dental Implants: A Comprehensive Review

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Abstract: Achieving the best aesthetic result is a key objective of implant-prosthetic therapy. To maximize the aesthetic outcome, ensuring that implant-supported restorations are in harmony with the peri-implant soft tissues and bone is essential. A comparative analysis of zirconia and titanium dental implants revealed that both materials offer high success rates; however, they present distinct advantages and limitations in clinical practice. Titanium implants, with surface modifications but without chemical composition changes, boast remarkable long-term survival. In contrast, zirconia implants, while presenting high aesthetic and biocompatibility qualities, have a relatively high incidence of material-specific failure, ranging from 4% to 2% after 5-10 years. While titanium implants generally show superior long-term performance, zirconia implants benefit from ongoing advancements aimed at improving their osseointegration and longevity. This study emphasizes the need for short-term and long-term studies, complemented by randomized controlled trials (RCTs), which are essential for optimizing implant materials and ensuring patient satisfaction. Continued innovation and research are crucial for advancing dental implant technology and enhancing the quality of life for patients requiring dental restorations. Finally, it is important to understand that all materials have both advantages and disadvantages, so the choice of the optimal material should be based on the specific purpose.

Keywords: dental implants; zirconia implants; titanium implants; implant success rates; long-term outcomes; material durability; osseointegration; implant technology; aesthetic implants; biocompatibility; implant longevity

1. Introduction

Achieving the best aesthetic result is a key objective of implant-prosthetic therapy. To maximize the aesthetic outcome, ensuring that implant-supported restorations are in harmony with the peri-implant soft tissues and bone is essential.

Titanium (Ti) is well known for its exceptional resistance to flexion and corrosion. Since the latter part of the twentieth century, it has been utilized in various industries, such as military, aerospace, sports equipment, and jewelry [1–3]. In the medical field, titanium is employed to manufacture pacemakers, endoprostheses, and stents. In implant dentistry, titanium is the preferred material for dental implants because of its biocompatibility, durability, and ability to integrate with bone, ensuring long-term implant stability [4]. Studies indicate that titanium implants have success rates ranging from 92.5% to 96.4% and survival rates between 94.7% and 99.4% over periods of at least five years [5,6].

Zirconia was originally discovered as a mineral in 1892 [7] and has been widely used as a refractory material for applications such as the outer wall of space shuttles owing to its high melting point of 2,715 °C. Zirconia has become a major ceramic material in dentistry over the past two decades because of its white color and sufficient mechanical strength. When we need to restore decayed teeth with an inlay or a crown, at present, we can choose metallic or ceramic prostheses by considering color and biocompatibility. This is because Zirconia is widely available for use in inlays, crowns, bridges, and abutments, which connect roots and artificial teeth in dental implants.

Over the past sixty years, both zirconia and titanium dental implants have been widely used, yet research comparing the two materials remains limited [8–17]. Previously, titanium and its alloys have been the preferred and widely accepted materials for dental implants for many years, with an extensive body of literature indicating high success rates. Titanium implants have long been considered the gold standard, and their effectiveness has been proven. However, zirconia implants have recently gained popularity because of their exceptional biocompatibility and mechanical properties. These implants provide alternative options that show promise and warrant further exploration.

Titanium offers excellent osteoconductivity and biomechanical properties, surpassing those of zirconia, which is renowned for its exceptional biocompatibility [19,20]. However, the advantages of titanium are offset by its association with metal-related allergies [21,22]. As a result, many researchers are advocating the adoption of zirconia ceramic implants as a 100% metal-free alternative to titanium in dental implant procedures [23,24]. While the use of zirconia ceramic implants in dental implant replacements is projected to continue to increase, there remains a dearth of reliable information concerning their fundamental properties, including implant fusion, biocompatibility, system design, percussion, and pulling forces [25,26]. Consequently, the establishment of comprehensive protocols for both the implantation technique and the use of zirconia ceramics as dental implant materials is imperative. Additionally, clear therapeutic criteria and standards must be developed to ensure optimal outcomes.

Comparing zirconia to titanium is akin to comparing ceramics to metals. Ceramics boast advantages such as high-temperature resistance, wear resistance, chemical stability, and, notably, white color for dentistry. However, they are also characterized by low fracture toughness or brittleness. In contrast, titanium offers high fracture toughness due to its strength and elongation, along with a good balance between rigidity and stiffness. The drawbacks of these materials include susceptibility to corrosion and fatigue. All materials have both advantages and disadvantages; no material is without flaws. This review aims to provide a scientific comparison of the biological and mechanical properties, aesthetics, cost, clinical performance, and long-term outcomes of zirconia and titanium implants.

2. Biological Properties

One of the primary goals of a dental implant is to seamlessly and effectively integrate with the surrounding bone and mucosal tissue once it is surgically placed in the highly complex and dynamic biological environment of the oral cavity. This intricate and delicate integration process, commonly referred to as "osseointegration," constitutes a vital component in establishing a direct and robust structural and functional connection between healthy bone tissue and the surface of load-bearing dental implants [25,26]. The successful achievement of both osseointegration and soft tissue integration plays a paramount role in ensuring the long-term success and excellent clinical outcomes of dental implant treatments [27].

While it is widely acknowledged that a multitude of diverse factors significantly influence the process of osseointegration in dental implants, it is imperative to underscore the pivotal role of the implant material itself as one of the paramount determinants of the implant's biological properties and subsequent clinical performance [28]. In recent years, tremendous strides have been made in the development and refinement of different types of implant materials that can be employed in dental implantology. These materials encompass a wide spectrum of options, including metallic materials, advanced ceramics, and innovative polymers, each possessing unique characteristics and attributes that render them suitable for specific clinical scenarios and patient requirements [29,30].

In the realm of metallic implant materials, commercially pure titanium [often referred to as cp-Ti] stands out as the gold standard owing to its exceptional strength, biocompatibility, and corrosion resistance. The use of cp-Ti for dental implants has consistently yielded remarkable outcomes and has been established as a reliable and efficacious choice for both clinicians and patients alike [31,32]. Nonetheless, it is imperative to acknowledge and address certain drawbacks and limitations associated with the use of titanium implants. These include the potential for allergic and hypersensitivity reactions triggered by the release of titanium metal ions in susceptible individuals, negative mucosal pigmentation that may occur in certain cases, and the inherent high density and

metallic luster of titanium implants, which can potentially compromise aesthetic outcomes in the anterior maxillary region, where optimal aesthetics are of utmost importance [33,34].

As global research endeavors to persistently advance and expand, professionals in the field of dental implantology are continually exploring and developing novel materials and innovative techniques that seek to overcome the existing limitations of titanium implants. Exciting breakthroughs have been made in recent years, with the introduction of alternative implant materials boasting impressive biocompatibility, enhanced esthetic properties, and a reduced risk of titanium-related complications [35,36]. By pushing boundaries of scientific knowledge and employing cutting-edge technologies, researchers and clinicians strive to revolutionize and optimize the field of dental implantology, ultimately offering patients the highest standard of care and the most favourable long-term clinical outcomes [10,37].

These new materials, such as zirconia and bioactive glasses, have revolutionized the field of dental implants. Zirconia, a biocompatible ceramic alternative to metallic implant materials, has gained considerable attention and popularity because of its tooth-like colour impressive mechanical properties, and superior esthetic outcomes. Its high strength and durability make it an excellent choice for implant-supported restorations, especially in the anterior region, where aesthetics are of utmost importance [9,38]. Bioactive glasses, on the other hand, offer unique advantages in terms of their ability to bond with bone and stimulate regeneration, thereby improving osseointegration and minimizing the risk of implant failure. These glasses, which are typically composed of a mixture of silicon, calcium, sodium, and phosphorus, have the remarkable ability to release bioactive ions when in contact with bodily fluids, encouraging bone growth and promoting the formation of a stable implant–bone interface [39,40]. Furthermore, bioactive glasses exhibit excellent biocompatibility, low toxicity, and resistance to bacterial colonization, making them attractive options for dental implant applications [11,41].

The development and utilization of these innovative materials signifies a paradigm shift in dental implantology, taking us one step closer to achieving optimal clinical outcomes and patient satisfaction. Additionally, advances in surface modification techniques have further enhanced the performance of dental implants. Researchers have successfully developed various surface modifications, such as nanostructured surfaces and coatings, that aim to promote faster and more reliable osseointegration. By manipulating the topography and chemistry of the implant surface, these modifications can effectively enhance cell adhesion, proliferation, and differentiation, ultimately leading to improved bone formation and integration [25,26]. Nanostructured surfaces, for example, demonstrate increased surface roughness and a greater surface area, facilitating greater contact with bone cells and promoting accelerated osseointegration. Coatings, on the other hand, can be applied to the implant surface to provide the necessary cues for cell signalling and adhesion. These coatings can be composed of biologically active substances, growth factors, and antimicrobial agents. When combined with traditional implant materials, they have the potential to revolutionize implant therapy by improving the success rate, reducing the healing period, and minimizing the risk of complications [27,28].

The continuous advancements in implant materials and surface modifications are paving the way for a new era of dental implantology, characterized by increased predictability, improved functionality, and enhanced patient satisfaction. As research progresses and new discoveries are made, even more innovative materials and techniques are expected to emerge, further expanding the possibilities and potential of dental implant treatments [29,30]. The future of dental implantology holds great promise, with the ultimate goal of providing patients with long-lasting, natural-looking, and highly functional restorations that mimic the form and function of natural teeth [10,37]. In conclusion, the integration of dental implants into the oral cavity is a complex and intricate process that relies on the implant material, surface modifications, and the body's natural healing mechanisms. Through continual research and innovation, the field of dental implantology is making significant strides in improving the outcomes and experiences of patients. With advancements in alternative materials, surface modifications, and treatment techniques, dental implant replacements will continue to evolve, offering patients a more predictable, esthetic, and functional solution for missing teeth [9,38].

In recent years, zirconia [ZrO₂] has been widely acknowledged and recognized as a highly promising and novel biomaterial for dental implant applications, primarily because of its exceptional

material properties. These properties include remarkable chemical and phase stability, outstanding fracture toughness, and outstanding biocompatibility [9,19]. As a result, zirconia has garnered significant attention and interest within the field of dentistry. In light of these compelling characteristics, various surface treatment methods have been proposed to further enhance and optimize the osseointegration process. These methods aim to augment the biological response and facilitate the integration of dental implants with the surrounding bone tissue [37,42]. Several techniques have shown promising results in this regard. One such technique involves the use of a sandblasting method, which creates controlled microroughness on the implant surface. This enhanced surface topography promotes cell adhesion and proliferation, stimulating bone-forming cell behavior and ultimately leading to improved osseointegration outcomes [26,30]. Another approach focuses on modifying the hydrophilic/hydrophobic surface wettability of zirconia. By altering the surface energy properties, the interaction of an implant with the biological environment can be enhanced. This modification has been proven to positively impact cell adhesion, proliferation, and differentiation, thereby facilitating the attachment of bone cells and promoting osseointegration [43,44]. Additionally, the introduction of stone disordering techniques has been proposed as a means to enhance the osseointegration process. By intentionally inducing disorder in the surface structure of zirconia, a higher surface free energy [SFE] is achieved. This augmented SFE plays a vital role in fostering bone-forming cell behavior and attachment, thereby facilitating the establishment of an intimate and robust connection between the implant and the surrounding bone tissue [20,39]. Furthermore, researchers have explored the utilization of a titanium layer in conjunction with zirconia implants. The deposition of a thin layer of titanium on the implant surface enhances its chemical properties and promotes improved cell adhesion and bone regeneration. This synergistic approach has demonstrated promising results in promoting osseointegration and achieving long-term implant success [9,19].

Moreover, the use of ultraviolet (UV) or visible light radiation has emerged as a potential method to enhance the osseointegration process. The exposure of zirconia implants to specific wavelengths of light has been shown to trigger biochemical and cellular responses, thereby promoting bone cell attachment, proliferation, and differentiation. The application of light radiation has the potential to significantly improve the integration of dental implants with the surrounding bone tissue [37,42].

In recent years, researchers have explored the combination and utilization of multiple treatment techniques to further enhance the osseointegration of zirconia-based biomaterials. The synergistic effects resulting from the combination of two or more strategies have shown great promise in significantly improving implant integration and the overall success of dental implant procedures [26,30].

In summary, the utilization of zirconia as a biomaterial for dental implants holds tremendous potential and promise in the field of dentistry. Through various surface treatment methods, such as sandblasting, hydrophilic/hydrophobic surface modification, stone disordering, titanium layer application, and light radiation, the osseointegration process can be improved, leading to superior clinical outcomes and patient satisfaction. Continued research and exploration in this field will likely pave the way for further advancements and breakthroughs, ultimately revolutionizing the field of dental implantology [43,44].

3. Osseointegration

Osseointegration, a term initially introduced by the eminent Albrektsson and Bregnemark, profoundly characterizes a specific state wherein direct and intimate contact is established between the remarkably engineered implant surface and the intricate bone tissue, devoid of even the slightest presence of interposed connective tissue [26,34]. This indispensable condition represents a dynamic interplay of intricate biological processes that intricately facilitate the coexistence of the implant surface within the biological environment and the intricate vascular meshwork of the vibrant living bone tissue, constituting a process that can span a considerable length of time, typically ranging anywhere between three- to six-month durations, contingent upon several factors, such as the precise anatomical location, the detailed medical history of patients, the pertinent biotype, and, last but not least, the inherent quality of the underlying bone tissue [27,45,46].

Upon scrutinizing the vast expanse of available literature, one would undoubtedly glean that this groundbreaking concept was initially tacitly alluded to by the esteemed Branemark, who

compellingly postulated that the phenomenon of osseointegration undoubtedly represents an inseparable, indissoluble interface, which aptly and eloquently finds its pertinent application to the impressive anchor-tissue zone that encircles the hydroxyapatite-coated subperiosteal implants [29,47,48].

A few years into extensive research at the end of the 20th century and heading into the new millennium in 2000, the focus of well-established zirconia brands shifted towards the remarkable biological properties possessed by these immensely successful dental implants [49]. Simultaneously, they also began to question the degree of wear and tear on the implants caused by abrasion [50]. As the demand for these implants soared, newer brands of zirconia emerged, flooding the market with an array of options [51]. However, despite this influx of options, the *in vivo* osteointegrative properties of zirconia implants have yet to be compared with those of titanium implants [8]. While extensive research has been conducted on the properties of these implants, including allergic analyses, their biological aspects take center stage in this context, leveraging the literature-based information available on zirconia implants [52].

Additionally, zirconia and titanium are head-to-head in the realm of adhesive dentistry. Surprisingly, even to date, the production of a reliable zirconia luting product has eluded researchers, thus highlighting the need for focused research in this area [10]. Furthermore, it should be emphasized that the success of dental implants relies heavily on the proper cementation of crowns and mobile prostheses in the oral cavity, as this crucial step plays a pivotal role in preventing implant failure [53]. The subsequent process of implant osseointegration lays the foundation for subgingival zirconia trials [54]. In the early 2000s, there was a significant surge of interest in the utilization of zirconia for full-arch prostheses. Rigorous research has been conducted to support the use of zirconia as a viable alternative to porcelain-fused-to-metal full-arch implant superstructures. Data acquired from laboratory experiments, clinical studies, and finite element analysis demonstrated exceptional clinical performance, ensuring patient comfort and maintaining marginal bone levels with the greatest effectiveness [18,55].

4. Mechanical Properties of Implants

Structural and mechanical properties play crucial roles in determining the characteristics of a material. For example, the elastic modulus, also known as the stiffness, is a key indicator of a material's structural properties [56]. In regard to titanium, its mechanical grade surpasses that of raw titanium, making it a preferred choice [57]. In the case of a titanium implant, when stress is applied, the material initially experiences elastic deformation. However, if the stress gradually increases and reaches the fatigue limit or fatigue strength, plastic deformation may occur [58]. Strength is a fundamental aspect of a material's ability to withstand applied loads. This quality depends on various factors, including flexibility, hardness, and ductility. Each of these elements significantly contributes to the overall strength of the material [59]. In fact, the ductility of a material contributes to its hardness. Hardness, in turn, refers to a material's resistance to indentation, an essential characteristic when evaluating the stability of an implant [60]. Moreover, hardness is directly linked to a material's ability to resist wear and tear in the oral environment, making hardness a critical property to consider [61,62]. The ability to obtain an implant material that can effectively replace titanium, which has exceedingly high mechanical performance in the oral cavity, is undeniably the pinnacle of interest. This represents a remarkable achievement in the field of dentistry, as it would revolutionize the way implants are perceived and utilized [63]. However, the journey towards discovering alternative implant materials is not easy. It is a challenging and arduous task that requires unwavering dedication and the relentless pursuit of excellence [64]. The key obstacle in finding a suitable substitute for titanium lies in the need for immense strength and durability. The long-term success of dental implants is intricately intertwined with their mechanical robustness [65].

It is imperative to recognize the fundamental disparity between metals and ceramics in this realm. Metals possess unique characteristics that allow them to withstand crack propagation, making them less prone to brittleness [56,57]. On the other hand, ceramics, although aesthetically pleasing and biocompatible, can be inherently fragile, posing potential risks in the context of oral implants [58]. In light of this substantial discrepancy, zirconia has emerged as the paramount choice for prosthetic applications. Its superior mechanical performance and unparalleled characteristics make it a favoured material over alumina in regard to prosthetic treatments [59,60]. Zirconia offers a perfect

balance between strength and aesthetics, making it an ideal candidate for dental implants. Its remarkable ability to resist crack propagation and maintain its structural integrity over time makes it a highly reliable material for long-term use in the oral cavity [61]. To evaluate the mechanical properties of loaded implants, a comprehensive assessment of various key mechanical properties is necessary [62]. This thorough exploration and assessment will shed light on the application of force on both zirconia and titanium implants. By analysing and comparing these properties, invaluable insights can be obtained, providing a clearer understanding of the performance and efficacy of these materials in clinical applications [63,64].

In conclusion, the search for an implant material that can effectively replace titanium is a noble pursuit. The demands for high mechanical performance and long-term success necessitate the identification of a suitable alternative. Zirconia, owing to its exceptional mechanical properties and unmatched characteristics, stands out as the material of choice for prosthetic applications. Through a thorough evaluation of key mechanical properties, a deeper understanding of the performance of zirconia and titanium implants can be achieved, paving the way for improved clinical outcomes and patient satisfaction [66–71].

5. Strength and Flexibility

The high density of titanium (Ti) results in a tensile strength of 350–550 megapascals [MPa], making it the most recommended dental implant in stress-bearing regions [72,73]. Maximum occlusal forces of approximately 200–300 Newtons [N] can be sustained by an implant in the posterior maxilla, whereas approximately 200–500 N can be sustained between the mandibular implants in the anterior regions [74,75]. The strength of yttria-stabilized tetragonal zirconia polycrystals [Y-TZP] is affected mainly by yttria-stabilized molecular stress [Y₂O₃], which tends to transform it into a cubic phase from a tetragonal phase, resulting in the in situ creation of compressive molecular stress [76]. This not only strengthens the implant by creating a compressive layer on the surface but also retards and drains the growing stress when the crack propagates [77]. Flexural strength implies the capacity for a material to sustain the load without experiencing permanent deformation [78]. Fracture leads to load release, which reduces the risk of abrupt, clinically relevant failure [79]. Overall, the properties of Ti and Y-TZP make them highly suitable for dental implant applications in stress-bearing regions, ensuring long-term stability and functionality [80,81]. Data from in vivo studies testing the mean width of a crack upon surface retrieval after a loading cycle show that surface contact cracks also occur on the zirconium oxide implant [15]. Additionally, recent findings have revealed that these cracks have a median size of 730 μm , providing further confirmation of the multiple ultramorphologic observations that have shown substantial evidence of some deterioration at the ZAS [Zirconia–Alumina–Silica] interface [19]. Notably, these observations align perfectly with prior scholarly research [82]. Notably, the strength of zirconia ensures that the surfaces do not easily scratch or chip, which greatly contributes to the ability of zirconia-based ultimate dental implants (ZUDIs) to sustain high occlusal forces [83]. This remarkable result is consistent with the extensive body of literature on the subject matter [84]. Moreover, the minimum flexural strength of zirconium oxide implants evaluated was found to be an impressive 350 MPa [85]. These compelling data not only validate the exceptional mechanical properties of zirconium implants, including their tensile strength and elastic modulus but also guarantee their biosafety [86,87]. In light of these remarkable findings, zirconia dental implants are clearly unquestionably appropriate for use in oral and maxillofacial surgery [88,89]. The ability of these implants to withstand substantial occlusal forces, coupled with their exceptional mechanical properties, further reinforces their suitability and efficacy in various dental applications.

6. Aesthetics

The aesthetics of dental implants and their related restorations can be defined in terms of their optical, touch, and surface properties [90,91]. The choice of material for dental implants is crucial, as titanium and titanium alloys are known to cause discoloration of the peri-implant mucosa and potentially increase bone loss [92,93]. When the appropriate implant material is selected, it is important for the attending physician to carefully consider the patient's clinical situation, as well as the topography and physiology of the patient [94,95]. Factors such as the experience of the clinician and the patient's preferences also play a significant role in this decision-making process [96]. In some

cases, the clinician may opt for the restoration or the use of zirconia implants to achieve a more aesthetically pleasing outcome [97–99]. Zirconia implants are known for their excellent biocompatibility and tooth-like appearance, making them an ideal choice for patients seeking a natural-looking smile [100,101]. These implants are made from zirconium oxide, a material that closely mimics the color and translucency of natural teeth [98,102]. With zirconia implants, patients can enjoy improved confidence and self-esteem because their new teeth blend seamlessly with their existing dentition [95,97,99]. Furthermore, the touch and surface properties of dental implants also contribute to overall aesthetics. A smooth and glossy surface can enhance the appearance and feeling of the implant, providing a more natural look and improving patient comfort [94,103,104]. Surface modification techniques, such as textured and porous coatings, can be utilized to optimize osseointegration and soft tissue attachment [100,101]. These modifications not only promote better integration of the implant but also allow for a more harmonious aesthetic outcome. The texture of the implant surface can be carefully selected to match the patient's natural dentition, ensuring a seamless blend between the implant and surrounding teeth [98,102]. Considering all of these factors, the clinician must approach each patient individually and tailor the treatment plan to meet the unique needs and desires of the patient [99]. The experience and expertise of the clinician are crucial in achieving a successful and aesthetically pleasing outcome. By taking into account the patient's clinical condition, anatomical considerations, and personal preferences, the clinician can ensure the selection of the most appropriate implant material and restoration technique [100,101]. The goal is to provide patients with a permanent dental solution that not only restores function but also enhances their smile and overall facial aesthetics [103,104]. With advancements in dental implant technology and materials, patients can have access to solutions that not only improve their oral health but also increase their confidence and improve their quality of life [90,91]. The use of lysine for a certain application depends on the thermal affinity of the polymer for superior transmittance and particularly low opacity, which means that on a solid material or a biaxially formed sheet, the more dispersed the particles are when exposed to light, the less representative the colour is. Dietmar et al. summarized the black classification pulse by CoJet, which should eliminate the interaction of particles in the area. Compared with non-radiation, the incorporation of radiation causes a change in colour which is usually light ideal, and a size of less than 10 nm, at which the whitening of the CoJet results in the highest hardness and strength and the lowest viscosity [105–114]. In a one-year study of patients 18–72 months postocclusal splinting, 73 splints were randomly split into two groups. The article was published in 1997 and was edited thereafter. Bruxogold [Degranulated C]. In the CoJet study, the original optical properties of the experiment can be maintained. Notably, the thermal affinity of lysine in various applications plays a significant role. The superior transmittance and low opacity of the polymer are crucial factors to consider. Specifically, when dealing with solid materials or biaxially formed sheets, achieving greater dispersion of particles upon light exposure is essential for accurate color representation. Dietmar et al. conducted a comprehensive examination of the CoJet black classification pulse, emphasizing the importance of minimizing particle interactions in a given area [105]. By incorporating radiation, an alteration in color occurs, ideally resulting in light hues. Furthermore, the CoJet process ensures that whitening, which takes place at a wavelength of less than 10 nm, enhances hardness and strength and reduces viscosity compared with nonradiation scenarios [106,107]. In a posttesting Clinical Arizona study conducted on patients who underwent occlusal splinting 18–72 months prior, 73 splints were randomly divided into two groups [108,109]. The study, initially published in 1997, has undergone subsequent editing to refine its findings [110]. Notably, Bruxogold [Degranulated C] was used [111]. Within the scope of the CoJet study, the original optical properties of the experiment can be consistently maintained, ensuring reliable results and insights [112–114].

7. Cost Considerations

Material metals, including a wide range of materials such as titanium, stainless steel, and pure zirconia, are commonly applied in the dental field because of their exceptional properties. Zirconia, in particular, is renowned for its remarkably high toughness, fracture strength, and biocompatibility, making it a preferred choice among dentists and patients alike [9,37]. Moreover, when considering the overall price of dental implants, it is crucial for patients to account for potential future replacement implant costs, adjustments, or necessary modifications [55]. It is also essential to consider

the potential loss of income that may arise from implant failure, as patients may experience difficulties in eating, speaking, or gaining self-confidence [115,116]. These crucial factors, supported by extensive research conducted by Chen et al., emphasize the importance of carefully considering the long-term implications and benefits of investing in high-quality dental materials and implants for optimal oral health and overall well-being [10,36,117–119].

8. Manufacturing Cost

There are three types of zirconia implants used in clinical situations: a maximum sintering temperature of 1100 °C [zirconia typically 3–4 mol% yttria containing partially stabilized zirconia, PS 23]; a maximum sintering temperature of 1200 °C [zirconia YZP with yttria and zirconia stabilizer totaling 8 mol%, PS8]; and a maximum sintering temperature of 1500 °C [zirconia YZP with zirconia stabilizer 12 mol% and 2 mol% Al₂O₃, PZ 12] [85,120]. The Zr-PS 8 process is the most expensive. Titanium mandible implants are produced in various sections by casting, a method that is more complex than manufacturing zirconia implants [121]. Additionally, zirconia, despite its low thermal conductivity, is challenging to work with. Initially, its brittle nature means that it can only be machined when fully sintered, whereas 'green' unsintered zirconia is easy to contour into very simple shapes. Zirconia dust must be used within minutes of processing and should be removed immediately after the surgical operation begins [122,123]. Unlike traditional titanium implants, zirconia implants are sintered before machining. The cost of manufacturing can be influenced by advanced techniques such as 3D printing or robotic machining. A systematic literature review by D3 revealed that using 3D-printed implants can result in cost savings ranging from 39% to 59% compared with machined implants, depending on the complexity of the case and the stage of implant development [124]. The complexity of bottom implants, primarily due to angling factors, further contributes to higher manufacturing costs. For example, the PT6 implant costs approximately 211% of the machining costs of PT20 and 148% of the printing costs of PT20 [125,126]. The overall cost of long-term dental implants, as outlined by current guidelines, typically falls within the range of \$2000–\$2025. When the survival rates of plastic and metal implants are compared, the projected lifespan of zirconia dental implants is approximately 34.86–35 years. Notably, there was a significant improvement in the short-term survival rates of all-resealable zirconia implants, increasing from 86.7% to 96.2% within a 5-year period. Similarly, the 10-year survival rates have improved by 8%, increasing from 86.7% to 94.6% [127]. However, these advancements are specific to short-term implantation and do not show variations in long-term implantation rates when the two materials are compared. This conclusion is based on an analysis of 40,646 transplants. Zirconia implants of higher cost might be more appealing in posterior locations than in anterior locations [128]. Additionally, factors such as oral hygiene, overall health, the skill of the dentist, and the quality of materials used can influence the success of a dental implant. There has been an increased emphasis on long-term follow-up care for dental implant patients to ensure optimal outcomes. Regular check-ups, professional cleaning, and maintenance procedures can greatly increase the longevity and success of dental implants. Advancements in technology and materials, such as computer-aided design and manufacturing techniques and the use of growth factors and biomaterials, have shown promising results in promoting tissue regeneration and improving overall implant success rates [129,130].

9. Clinical Performance

In complex in vivo situations, such as those found in medical scenarios involving the interaction of materials with living tissue, the tissue response plays a pivotal and critical role. The surface microstructure of implants serves as a key determinant of both the rate and outcome of therapy [131,132]. Therefore, when developing clinical implant surfaces, the primary objective should be to effectively and consistently control the quality and pace of connective tissue attachment. This control is of utmost importance, as it promotes the establishment of an epithelial seal, enabling apical soft tissue inflammation to transform into more mature and healthier connective tissue [133,134]. In turn, this transformation facilitates the enhancement and long-term stability of the clinical outcomes. To obtain meaningful and accurate clinical outcome data, it is imperative to conduct long-term studies. These studies should involve the placement of single- and multiple-unit restorations in patients with less-than-ideal medical histories [135]. Furthermore, it is essential to involve a diverse group of dental practitioners who utilize various restoration methods and varying numbers of implants per jaw [136].

Fortunately, a vast and extensive body of data exists, shedding light on the success rates of such treatments. These data, derived from routine cases encountered in clinical practice in unselected patients, demonstrate treatment success rates ranging from an impressive 98.4% to a flawless 100% even after 14 years [137,138]. The comprehensive nature of these studies encompasses a wide range of clinical practices, providing reassurance regarding the efficacy and reliability of implant treatments across diverse patient populations. To ensure optimal long-term outcomes and success rates of clinical implant surfaces, it is crucial to focus on meticulous and consistent control over the quality and pace of connective tissue attachment. This approach is especially crucial in medical scenarios involving the interaction of materials with living tissue, such as those encountered in various medical procedures [139,140]. By prioritizing the establishment of a well-integrated epithelial seal, it becomes possible for apical soft tissue inflammation to undergo transformative processes and develop into healthier and more mature connective tissue. This transformative process greatly contributes to the overall enhancement and long-term stability of clinical outcomes, leading to improved patient satisfaction and successful therapy [131]. Both zirconia and titanium implants have been extensively studied, and the results show exceptionally high long-term clinical success rates. The survival rate of implants as an indicator of their performance reveals that adverse events are incredibly rare, with the majority of patients experiencing very positive implant–tissue responses [141]. The satisfaction levels among patients who have received both types of implants are generally quite high. However, zirconia ceramic implants have been reported to sometimes encounter issues during osseointegration, a crucial process for ensuring the stability and long-term success of the implant [123]. Therefore, understanding the factors that contribute to the clinical success of synthetic implant materials is highly important. Numerous studies have highlighted the importance of the interface between the implant material and the surrounding tissues in determining the overall success of the implant [142,143]. Additionally, the durability of the material itself plays a crucial role in its long-term performance. The composition of the implant material is particularly influential in terms of both its surface characteristics and bulk material properties [144]. To address these challenges, recent research has focused on utilizing network chalcones to enhance zirconia implants. These chalcones facilitate the attachment of important minerals, such as calcium and phosphorus, as well as other beneficial metal ions to the surfaces of the implants [145]. This innovative approach holds great potential in enhancing the osseointegration process and improving the overall durability of zirconia implants. As we strive to offer the best possible dental solutions, it is essential to manage any factors that may contribute to the accumulation of harmful substances around the implants [146]. By carefully considering the material composition, optimizing the biological interaction at the material/tissue interface, and prioritizing the long-term durability of the implants, we can ensure that successful implants continue to be a reliable and beneficial option for dental patients. The incorporation of network chalcones represents a significant advancement in the field of implant dentistry, providing a promising avenue for further research and development [147]. It offers the potential to revolutionize the way we approach implant materials, providing improved outcomes for patients in terms of both functionality and longevity. Furthermore, ongoing studies are investigating the potential of combining zirconia and titanium implants to capitalize on the unique advantages of each material. This multimaterial approach aims to optimize the performance of dental implants by leveraging the strengths of both zirconia and titanium [148]. Preliminary findings suggest that the combination of these materials may result in enhanced osseointegration and improved long-term stability. The ability to tailor implant materials on the basis of patient-specific factors opens a whole new realm of possibilities in dental implantology, paving the way for personalized treatment plans that maximize outcomes. In conclusion, the field of dental implantology continues to evolve and innovate, driven by the pursuit of excellence in patient care. The success rates of zirconia and titanium implants are well documented, with zirconia implants benefiting from recent advancements in material enhancement through network chalcones. By understanding the importance of the implant–tissue interface, optimizing material composition, and embracing emerging technologies, we can ensure that dental implants remain a reliable and successful treatment option for patients. With ongoing research and development, the future holds great promise for even further advancements in the world of dental implantology, ultimately improving the lives of countless individuals worldwide [145,149].

10. Long-Term Success Rates

Although the outcomes before or at prosthetic loading are critical factors for evaluating implant success, long-term sustained performance is fundamentally relevant for both interventions and comparisons. Long-term complications and the likelihood of the restoration or implant requiring replacement can considerably affect average costs and, consequently, considerations of health economics as well as patient psychological distress [150,151]. Both titanium and zirconia dental implants have extremely high success rates in most patients. The long-term (greater than 60 months) prospective survival rates of titanium surface-modified implants without chemical composition modification are at least 99.9% [152]. The few zirconia implants presented material-specific failures after 5–10 years [4–2% cumulative incidence] [153]. However, the study of longitudinal outcomes of periodontally healthy individuals is needed because studies conducted in compromised patients might not reflect the actual high rate of titanium or zirconia integration due to the condition of the study population [9,154]. Additionally, some authors discuss important aspects that can affect long-term implant success or a patient's perception of success, including standard or customized abutments; provisional, single-unit, immediate placement; 1-stage, and 2-stage procedures for single and multiple extractions immediately or in delayed loading; and the use of bone augmentation and soft tissue management [155,156]. Furthermore, evaluating the impact of patient compliance and adherence to postoperative care instructions is crucial, as compliance can greatly influence the long-term outcomes of dental implants [157]. Proper oral hygiene practices, regular dental check-ups, and the avoidance of harmful habits such as smoking or excessive alcohol consumption can significantly contribute to the sustainability and success of dental implant treatments [158]. Moreover, advancements in technology and implant design have led to the development of innovative techniques and materials that can increase the longevity and functionality of dental implants [151]. For example, the use of computer-aided design and manufacturing [CAD/CAM] technology allows for the precise customization of abutments and prosthetic components, leading to improved fit and stability [150]. Additionally, the utilization of biocompatible materials and surface modifications has shown promising results in promoting osseointegration and reducing the risk of implant failure [152]. These advancements not only increase the overall success rate of dental implants but also provide patients with aesthetically pleasing and functional restorations that can significantly improve their quality of life [153]. However, it is important to note that individual factors such as systemic health conditions, bone quality, and occlusal forces can also impact the long-term performance of dental implants [154]. Therefore, a comprehensive evaluation of each patient's unique characteristics and needs is essential in determining the most appropriate treatment approach and ensuring optimal long-term outcomes [9]. By considering all these factors and implementing evidence-based practices, dental professionals can effectively maximize the success and durability of dental implant treatments, thereby improving patient satisfaction and overall oral health [155].

Overall, the findings from the short-term studies, which did not include randomized controlled trial (RCT) data, only revealed the survival rates of the materials used. On the other hand, long-term studies, which were not RCTs but were free from bias, reported success rates and the survival of the implants. Notably, there were noticeable rates of material failure ranging from 4% to 11.5% within a period of 1–10 years for zirconia implants [159]. Additionally, the cumulative success rates for implants, predominantly titanium-based, with or without surface modifications, ranged from 87.1% to 92% over a span of 10 to 12.3 years in individuals suffering from periodontal disease [160]. Importantly, these implants are subjected to frequent attacks from masticatory forces. Moreover, over time, implants may experience mechanical fatigue [161]. Currently, there are implant systems that have been functioning for approximately 8.0 years, whereas others have been successfully implanted for a duration of 7.86 years [162]. These findings highlight the crucial importance of conducting both short-term and long-term studies to gain a comprehensive understanding of implant success and survival rates. While short-term studies provide valuable insights into immediate material performance, long-term studies offer a more accurate representation of implant durability over extended periods [163]. The absence of RCT data in short-term studies does not undermine their significance, as they still contribute valuable information regarding material survival rates. Furthermore, the observed rates of material failure for zirconia implants within a 1-- to 10-year timeframe warrant careful consideration [164]. While zirconia implants have gained popularity for their superior aesthetic qualities and biocompatibility, these findings suggest that their long-term

durability may be a concern. Additionally, the variation in cumulative success rates for titanium-based implants underscores the need for further investigation into surface modifications that may increase their longevity and performance [165]. Notably, masticatory forces pose a significant challenge to implant longevity. The constant pressure exerted on the implants during chewing and biting can gradually weaken their structure, potentially leading to mechanical fatigue and, ultimately, implant failure [166]. This emphasizes the importance of designing implant systems that can withstand these forces and maintain their integrity over time. Despite these challenges, the current state of implant technology is promising. With some systems having been successfully functional for approximately 8.0 years and others reaching a duration of 7.86 years, advancements in implant materials and designs are steadily improving their longevity [18]. However, continuous research and development efforts should remain a priority to ensure even greater success rates and extended lifespans for dental implants [167]. In conclusion, the combination of short-term and long-term studies, free from bias and encompassing RCT data, is essential for a comprehensive understanding of implant performance. The rates of material failure for zirconia implants and the variation in success rates for titanium-based implants underscore the challenges that must be addressed to increase implant durability. The impact of masticatory forces and mechanical fatigue further emphasizes the need for resilient implant systems. Nevertheless, the progress made thus far is promising, and continued advancements in implant technology hold the potential to revolutionize the field of dentistry and improve the quality of life for individuals requiring dental implants [159,160].

11. Conclusions

Ceramics, such as zirconia, offer advantages like high-temperature resistance, wear resistance, chemical stability, and a white color that is particularly beneficial in dentistry. However, ceramics also have drawbacks, such as low fracture toughness and brittleness. Conversely, metals like titanium provide high fracture toughness due to their strength and elongation, along with a good balance between rigidity and stiffness, but they are prone to corrosion and fatigue.

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