MEDICINE AND MATERIALS
Volume 5, Issue 4, 2025: 233-242 ISSN: 2784 – 1499 & e-ISSN: 2784 – 1537
DOI: 10.36868/MEDMATER.2025.05.04.07 | www.medicineandmaterials.com |

BIOCOMPATIBILITY AND MECHANICAL PERFORMANCE OF DENTAL IMPLANT MATERIALS: TITANIUM, TITANIUM–ZIRCONIUM ALLOYS AND ZIRCONIA

Andrei MOSTOVEI [1], Ramona FEIER[2,*], Oleg SOLOMON[1]

[1] Nicolae Testemitanu State University of Medicine and Pharmacy, Chisinau, the Republic of Moldova.
[2] „Dimitrie Cantemir" University, Faculty of Medicine, Târgu Mureș, România.

Abstract

The long-term success of dental implant therapy is critically dependent on the biocompatibility and mechanical performance of the materials used in implant systems. Over time, dental implantology has evolved from early experimental concepts toward biologically integrated and mechanically reliable solutions. This narrative review examines the principal dental implant materials currently in use, with a specific focus on titanium, titanium–zirconium alloys, and zirconia. The biological behavior of these materials is discussed in relation to osseointegration, tissue response, and corrosion resistance, while their mechanical performance is analyzed in terms of strength, fracture resistance, and long-term stability under functional loading. Titanium remains the reference material due to its well-documented clinical reliability and favorable balance between mechanical and biological properties. Titanium–zirconium alloys have expanded clinical indications by offering enhanced mechanical strength for narrow-diameter implants without compromising biocompatibility. Zirconia implants present a metal-free alternative with promising biological and esthetic characteristics, although their mechanical behavior requires careful clinical consideration. The review highlights the importance of rational material selection based on patient-specific anatomical, functional, and biological factors. An integrated understanding of material science and clinical performance is essential for optimizing implant outcomes and ensuring predictable long-term success in modern dental implantology.
Keywords: dental implants, biocompatibility, mechanical performance, titanium alloys, zirconia

Introduction

Dental implantology has undergone a profound transformation over the past decades, driven by the continuous search for materials that optimally combine biocompatibility, mechanical reliability, and long-term clinical stability. Early concepts in dental implants were primarily experimental, focusing on empirical approaches rather than a comprehensive understanding of tissue–material interactions. Hulbert and Bennett highlighted, as early as the mid-1970s, that the success of dental implants depends fundamentally on the biological acceptance of the material and its capacity to withstand functional loads within the oral environment [1]. This foundational perspective established the basis for modern biomaterial-oriented implant research.

Corresponding author: dr.ramonafeier@yahoo.ro

The concept of biocompatibility evolved alongside advancements in material science. Lemons emphasized that dental implant biomaterials must not only be inert but also capable of eliciting a favorable biological response, particularly at the bone–implant interface [2]. This paradigm shift moved implantology beyond mere mechanical anchorage toward biological integration, later conceptualized as osseointegration. Concurrently, experimental studies began exploring alternative materials, including polymers, to assess their potential as implant substrates.

Early investigations into polymer-based implants demonstrated both the ambition and limitations of non-metallic materials. Carvalho et al. provided histologic and histometric evidence showing that polyurethane resin implants induced variable bone healing responses in experimental models, revealing challenges related to material stability and tissue compatibility [3]. These findings underscored the difficulty of achieving predictable osseointegration with polymeric materials and highlighted the importance of surface characteristics and mechanical properties in guiding tissue response.

As implantology matured, attention increasingly focused on materials capable of combining biological tolerance with superior mechanical performance. Ceramic-based materials, particularly zirconia, emerged as promising candidates. Adatia et al. demonstrated that yttria-stabilized zirconia abutments exhibit high fracture resistance, supporting their potential use in load-bearing implant components [4]. This work marked a critical step toward validating ceramic materials not only from an esthetic standpoint but also from a biomechanical perspective.

Parallel to ceramic developments, alloy engineering significantly advanced implant design. Titanium–zirconium alloys were introduced to enhance mechanical strength while preserving the biocompatibility associated with commercially pure titanium. Chiapasco et al. reported favorable clinical outcomes using narrow-diameter titanium–zirconium implants in patients with horizontally deficient ridges, highlighting improved mechanical performance without compromising biological response [5]. These findings reinforced the role of alloy optimization in addressing anatomical and functional limitations.

Historically, polymer implant concepts played a crucial exploratory role in shaping implant research. Hodosh et al. proposed the dental polymer implant concept, reflecting early attempts to identify materials with elastic moduli closer to that of bone [6]. Although ultimately limited by insufficient mechanical strength and long-term stability, these approaches contributed valuable insights into the importance of biomechanical compatibility.

Comprehensive reviews in the early 1990s consolidated existing knowledge and clarified clinical priorities. Meffert et al. emphasized that predictable implant success requires both biological integration and mechanical durability, framing implantology as an interdisciplinary field bridging periodontology, surgery, and materials science [7]. Similarly, Williams articulated fundamental principles governing biomaterial selection, stressing the need for materials to maintain chemical stability and mechanical integrity in the complex oral environment [8].

Despite the widespread adoption of titanium, concerns regarding electrochemical behavior and corrosion phenomena emerged. Ravnholt demonstrated that galvanic coupling between titanium and other dental alloys can induce corrosion currents and localized pH changes, potentially affecting peri-implant tissues [9]. These findings prompted further investigations into corrosion mechanisms and their biological implications.

As ceramic implants gained prominence, systematic evaluations of zirconia became increasingly relevant. Prithviraj et al. provided a comprehensive review of zirconia as an implant material, highlighting its favorable biocompatibility, low plaque affinity, and high strength, while also acknowledging limitations related to brittleness and long-term clinical data [10]. Complementary in vivo studies by Depprich et al. demonstrated comparable osseointegration between zirconia and titanium implants, reinforcing the biological viability of zirconia-based systems [11].

Broader overviews of dental implant biomaterials further contextualized these findings. Muddugangadhar et al. synthesized data on metals, ceramics, and polymers, emphasizing that no single material is universally ideal and that material selection must be guided by clinical indication and biomechanical demands [12]. Within this framework, corrosion resistance emerged as a key determinant of long-term implant success.

Chaturvedi provided a focused analysis of corrosion phenomena affecting titanium and its alloys, emphasizing their clinical relevance and potential impact on peri-implant health [13]. These concerns were expanded upon by Manivasagam et al., who discussed corrosion prevention strategies and highlighted surface modifications as essential tools for enhancing implant longevity [14]. Finally, Adya et al. systematically reviewed corrosion mechanisms in titanium dental implants, consolidating evidence that electrochemical stability is integral to both biocompatibility and mechanical performance [15].

Collectively, the evolution of dental implant biomaterials reflects a progressive refinement of material selection criteria, integrating biological compatibility, mechanical resilience, and chemical stability. This historical trajectory provides the foundation for contemporary comparative analyses of titanium, titanium–zirconium alloys, and zirconia as leading implant materials.

Biocompatibility of dental implant materials

Biocompatibility represents a fundamental prerequisite for the clinical success of dental implants, encompassing the ability of a material to perform its intended function without eliciting adverse local or systemic biological responses. Among metallic implant materials, titanium and its alloys have been extensively investigated due to their favorable biological behavior and chemical stability. Adya et al. highlighted that the biocompatibility of titanium implants is closely linked to their resistance to corrosion and the formation of a stable oxide layer, which limits ion release and inflammatory reactions in peri-implant tissues [15]. These properties underpin the long-standing clinical acceptance of titanium as a reference implant material.

Beyond metallic systems, the evolution of biomaterials has been guided by a deeper understanding of tissue–material interactions. Huebsch and Mooney emphasized that modern biomaterials are no longer designed to be merely inert but to actively support biological processes such as cell adhesion, proliferation, and differentiation [16]. This conceptual shift has influenced implant material development, encouraging the optimization of surface characteristics to enhance osseointegration and long-term tissue stability.

Historically, polymer-based implant materials were explored as potential alternatives to metals due to their elastic properties and ease of processing. Waerhaug and Zander investigated the implantation of acrylic roots in tooth sockets, demonstrating that although initial tissue tolerance could be achieved, long-term stability and integration were inconsistent [17]. These early findings revealed that adequate biocompatibility requires not only biological acceptance but also sufficient mechanical and chemical stability to maintain tissue health over time.

Further research into polymer implants examined the influence of processing techniques on biological response. Gettleman et al. demonstrated that rapid curing procedures could significantly alter the properties of polymer implant materials, affecting their structural integrity and potentially their interaction with surrounding tissues [18]. Similarly, Ashman reported variable clinical outcomes with acrylic resin tooth implants, reinforcing concerns regarding their long-term biocompatibility and mechanical reliability [19]. Collectively, these studies contributed to the gradual abandonment of polymers as primary load-bearing implant materials.

In contrast, ceramic materials—particularly zirconia—have gained increasing attention due to their favorable biological and esthetic properties. Özkurt and Kazazoğlu reviewed the available literature on zirconia dental implants, concluding that zirconia exhibits excellent soft tissue compatibility, low bacterial adhesion, and promising osseointegration potential [20]. These characteristics make zirconia an attractive alternative, especially in patients with high esthetic demands or metal sensitivities.

Comparative experimental studies have further clarified the biological performance of zirconia relative to titanium. Kohal et al. conducted an animal study demonstrating that custom-made zirconia and titanium implants subjected to functional loading exhibited similar levels of osseointegration [21]. This finding supports the notion that zirconia can achieve a biologically stable bone–implant interface comparable to that of titanium, provided that appropriate design and surface characteristics are employed.

Overall, the biocompatibility of dental implant materials is the result of complex interactions between material composition, surface properties, mechanical behavior, and the biological environment. While titanium remains the benchmark material due to its well-documented clinical performance, emerging evidence indicates that zirconia can offer comparable biological outcomes under specific conditions. The historical limitations of polymer-based implants further emphasize that true biocompatibility extends beyond initial tissue tolerance, requiring long-term stability and predictable integration within the oral environment.

Mechanical Performance of dental implant materials

Mechanical performance is a critical determinant of dental implant success, as implants are continuously subjected to complex functional loads generated during mastication, parafunction, and occlusal dynamics. An implant material must therefore exhibit adequate strength, stiffness, fracture resistance, and fatigue behavior to ensure long-term structural integrity. Early analyses of dental implant systems emphasized that insufficient mechanical stability inevitably compromises biological integration, regardless of initial tissue tolerance [1,7,12].

Titanium has long been regarded as the reference material in implantology due to its favorable balance between mechanical strength and elastic modulus. Its relatively low modulus of elasticity compared to other metals allows more physiological stress distribution to the surrounding bone, reducing stress shielding and marginal bone loss [2,8,12]. However, commercially pure titanium may present limitations in situations requiring reduced implant diameters or increased load-bearing capacity, prompting the development of titanium-based alloys.

Titanium–zirconium alloys represent a significant advancement in this context. Chiapasco et al. demonstrated that Ti–Zr narrow-diameter implants exhibit enhanced mechanical strength while maintaining clinical reliability in anatomically compromised ridges [5]. The improved tensile and fatigue resistance of these alloys enables their use in reduced bone volumes without increasing fracture risk, thus expanding treatment options while preserving biomechanical safety.

Ceramic materials, particularly yttria-stabilized zirconia, have been extensively evaluated for their mechanical performance in implant-related applications. Adatia et al. reported high fracture resistance values for zirconia implant abutments, indicating their capacity to withstand occlusal forces comparable to those tolerated by metallic components [4]. The transformation toughening mechanism inherent to zirconia contributes to crack resistance, partially compensating for its intrinsic brittleness.

Despite these advantages, the mechanical behavior of zirconia remains highly dependent on material processing, surface treatment, and design. Reviews focusing on zirconia implants emphasize that while their compressive strength is high, susceptibility to catastrophic fracture under tensile or bending stresses remains a concern, particularly in unfavorable loading conditions [10,20]. Consequently, careful case selection and prosthetic planning are essential when zirconia-based systems are employed.

The interaction between mechanical performance and chemical stability must also be considered. Corrosion-related phenomena in metallic implants can influence mechanical integrity over time. Studies have shown that electrochemical processes affecting titanium and its alloys may alter surface characteristics and contribute to material degradation, potentially impacting fatigue resistance [9,13,14,15]. These findings underscore the importance of long-term mechanical stability in conjunction with corrosion resistance.

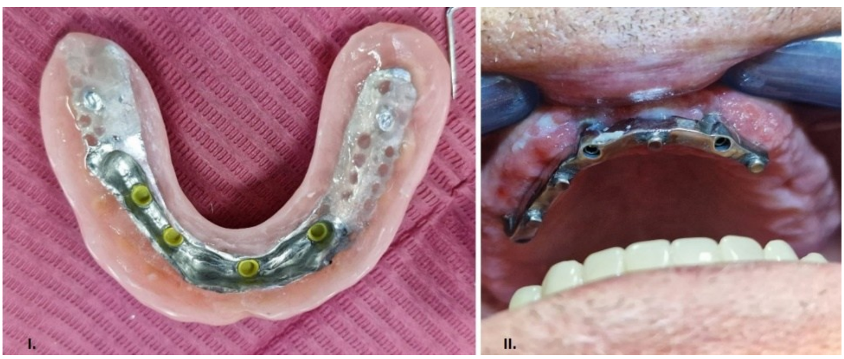

Figure 1. Clinical illustration of implant-supported prosthetic materials and structural design: (I) Mandibular implant-supported overdenture with metallic reinforcement bar embedded in an acrylic resin base, illustrating the structural role of metal components in improving mechanical stability and load distribution. (II) Intraoral view of the implant-supported bar framework, highlighting the direct interaction between metallic materials and peri-implant soft tissues.

The images are provided for illustrative purposes to support the discussion on the mechanical performance and biocompatibility of dental implant materials.

Comparative experimental data further suggest that, under controlled conditions, zirconia and titanium implants can demonstrate similar mechanical behavior when appropriately designed and loaded. Kohal et al. observed comparable osseointegration under functional loading for both materials in an animal model, indirectly supporting the adequacy of their mechanical performance in vivo [21]. Nevertheless, the long-term clinical predictability of zirconia implants continues to rely on ongoing optimization of material composition and implant geometry.

Corrosion resistance and long-term material stability

Corrosion resistance represents a critical factor influencing the long-term stability and biocompatibility of dental implant materials, particularly in the chemically complex and biologically active oral environment. Implants are continuously exposed to saliva, fluctuating pH levels, bacterial metabolites, and mechanical stresses, all of which can accelerate electrochemical degradation. Early studies emphasized that material degradation processes may compromise both mechanical integrity and peri-implant tissue health [8,12].

Titanium owes much of its clinical success to the formation of a stable and self-regenerating titanium oxide layer, which acts as a protective barrier against corrosion. However, this passive layer is not entirely immune to disruption. Ravnholt demonstrated that galvanic coupling between titanium and other dental alloys can generate corrosion currents and localized pH increases, potentially affecting surrounding tissues [9]. Such electrochemical interactions are particularly relevant in complex prosthetic reconstructions involving multiple metallic components.

Subsequent investigations have expanded on the clinical relevance of corrosion phenomena in titanium-based implants. Chaturvedi highlighted that corrosion processes may result in the release of titanium ions and particles, which can accumulate in peri-implant tissues and potentially trigger inflammatory responses [13]. These findings underscore the importance of considering electrochemical stability as an integral component of implant biocompatibility rather than a purely material science concern.

Further reviews have detailed the mechanisms underlying corrosion in biomedical implants, including fretting, crevice corrosion, and galvanic corrosion. Manivasagam et al. emphasized that mechanical loading and micromovements at the implant–abutment interface can exacerbate corrosion processes, thereby influencing long-term mechanical performance and structural integrity [14]. These interactions illustrate the close relationship between mechanical behavior and chemical stability in implant systems.

Adya et al. provided a comprehensive synthesis of corrosion-related issues specific to titanium dental implants, noting that surface modifications, alloy composition, and environmental factors all play decisive roles in corrosion resistance [15]. Their analysis supports the implementation of optimized surface treatments and careful material selection to minimize long-term degradation.

Compared to metallic materials, ceramic implants such as zirconia exhibit inherent resistance to electrochemical corrosion due to their non-metallic nature. Reviews focusing on zirconia implants have consistently reported minimal ion release and high chemical stability, contributing to favorable peri-implant soft tissue responses [10,20]. Nevertheless, while zirconia is largely unaffected by classical corrosion mechanisms, concerns remain regarding low-temperature degradation and surface phase transformations, which may indirectly influence mechanical reliability over extended periods.

In the context of long-term stability, corrosion resistance must be evaluated alongside fatigue behavior, surface integrity, and biological response. Experimental evidence suggests that when appropriately designed and clinically indicated, both titanium-based and zirconia implants can achieve satisfactory long-term performance. However, the potential for corrosion-related degradation in metallic systems highlights the importance of ongoing monitoring and material optimization [9,13,15].

Clinical Implications, material selection, and future perspectives

The selection of dental implant materials represents a critical clinical decision that must balance biological compatibility, mechanical reliability, and long-term stability within the oral environment. Titanium has remained the gold standard in implantology due to its predictable clinical performance, favorable osseointegration, and extensive long-term documentation. Reviews and overviews consistently emphasize that titanium implants offer a reliable balance between strength, corrosion resistance, and biological acceptance, making them suitable for the majority of clinical scenarios [2,7,8,12].

However, specific anatomical and functional challenges have necessitated the development of alternative material solutions. Titanium–zirconium alloys have emerged as a valuable option in cases requiring narrow-diameter implants or placement in compromised bone volumes. Clinical evidence demonstrates that these alloys provide enhanced mechanical strength without adversely affecting biocompatibility, thereby expanding treatment possibilities in patients with limited ridge dimensions or high functional demands [5]. From a clinical standpoint, this allows practitioners to reduce the need for extensive bone augmentation while maintaining mechanical safety.

Zirconia implants represent a distinct category, offering advantages primarily related to soft tissue response and esthetics. Literature reviews highlight zirconia's low plaque affinity, favorable mucosal integration, and absence of metallic ion release, making it particularly attractive for patients with metal sensitivities or high esthetic expectations [10,20]. Experimental studies further suggest that zirconia can achieve osseointegration levels comparable to titanium when appropriate implant design and loading protocols are applied [11,21]. Nevertheless, clinicians must carefully consider the material's brittleness and sensitivity to tensile stresses, especially in posterior regions subjected to high occlusal loads.

Historical experience with polymer-based implants provides an important clinical lesson. Although early polymer concepts aimed to achieve biomechanical compatibility with bone, long-term outcomes were limited by insufficient mechanical stability and inconsistent biological integration [6,17,19]. These findings underscore that material selection cannot rely solely on initial tissue tolerance but must account for long-term functional demands.

From a practical perspective, material choice should be guided by a comprehensive assessment of patient-specific factors, including bone quality, occlusal scheme, esthetic requirements, and systemic considerations. The interaction between corrosion resistance, mechanical performance, and biological response further reinforces the need for integrated treatment planning, particularly in complex prosthetic reconstructions involving multiple components [9,13,15].

Looking toward future perspectives, ongoing research continues to focus on optimizing implant materials through alloy refinement, surface modification, and improved processing techniques. Advances in biomaterial science aim to enhance both biological signaling and mechanical resilience, aligning with contemporary concepts of functional tissue integration rather than passive material tolerance [12,16].

Conclusion

The evolution of dental implant materials reflects a progressive integration of biological principles and mechanical requirements, with titanium establishing itself as the clinical benchmark due to its proven biocompatibility, corrosion resistance, and mechanical reliability. The development of titanium–zirconium alloys and zirconia-based systems represents a response to specific anatomical, functional, and esthetic challenges, demonstrating that implant success is fundamentally dependent on the balanced interaction between material composition, structural design, and the biological environment.

Contemporary evidence indicates that no single implant material can be universally applied across all clinical scenarios, emphasizing the necessity of individualized material selection based on biomechanical demands, tissue response, and long-term stability considerations. Titanium–zirconium alloys offer enhanced strength for reduced-diameter applications, while zirconia provides a metal-free alternative with favorable soft tissue behavior, provided that its mechanical limitations are carefully managed. Ultimately, the predictable success of implant therapy relies on an integrated understanding of material science, biological integration, and clinical indication, guiding evidence-based decision-making in modern implantology.

References

1. Cicciù M, Tallarico M. *Dental Implant Materials: Current State and Future Perspectives.* **Material***s*. 2021. 14,2,371. https://doi.org/10.3390/ma14020371
2. Marconcini S, Giammarinaro E, Toti P, Alfonsi F, Covani U, Barone A. *Longitudinal analysis on the effect of insertion torque on delayed single implants: A 3-year randomized clinical study*. **Clin. Implant Dent. Relat. Res**. 2018. 20,322–332. doi: 10.1111/cid.12586.
3. de Morais JPP, Pacheco IKC, Filho ALMM, Ferreira DCL, Viana FJC, da Silva Reis F, de Matos JME, Dos Santos Rizzo M, Fialho ACV. *Polyurethane derived from castor oil monoacylglyceride (Ricinus communis) for bone defects reconstruction: characterization and in vivo testing*. **J Mater Sci Mater Med.** 2021. 32,4,39. doi: 10.1007/s10856-021-06511-z
4. Adatia ND, Bayne SC, Cooper LF, Thompson JY. *Fracture resistance of yttria-stabilized zirconia dental implant abutments*. **J Prosthodont**. 2009. 18,17–22. doi: 10.1111/j.1532-849X.2008.00378.x

5. Chiapasco M, Casentini P, Zaniboni M, Corsi E, Anello T. *Titanium-zirconium alloy narrow-diameter implants (Straumann Roxolid(®)) for the rehabilitation of horizontally deficient edentulous ridges: prospective study on 18 consecutive patients*. **Clin Oral Implants Res**. 2012;23:1136–1141. doi: 10.1111/j.1600-0501.2011.02296.x
6. Najeeb S, Zafar MS, Khurshid Z, Siddiqui F. *Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics*. **J Prosthodont Res**. 2016. 60,12-9. doi: 10.1016/j.jpor.2015.10.001.
7. Guillaume B. *Dental implants: A review*. **Morphologie.** 2016. 100,331,189-198. doi: 10.1016/j.morpho.2016.02.002.
8. Hakim LK, Yari A, Nikparto N, Mehraban SH, Cheperli S, Asadi A, Darehdor AA, Nezaminia S, Dortaj D, Nazari Y, Dehghan M, Hojjat P, Mohajeri M, Hasani Jebelli MS. *The current applications of nano and biomaterials in drug delivery of dental implant*. **BMC Oral Health.** 2024 Jan. 24,1,126. doi: 10.1186/s12903-024-03911-9.
9. Ravnholt G. *Corrosion current and pH rise around titanium coupled to dental alloys*. **Scand J Dent Res**. 1988. 96,466–472. doi: 10.1111/j.1600-0722.1988.tb01585.x.
10. Prithviraj DR, Deeksha S, Regish KM, Anoop N. *A systematic review of zirconia as an implant material*. **Indian J Dent Res**. 2012. 23,643–649. doi: 10.4103/0970-9290.107383
11. Depprich R, Zipprich H, Ommerborn M, Naujoks C, Wiesmann HP, Kiattavorncharoen S, Lauer HC, Meyer U, Kübler NR, Handschel J. *Osseointegration of zirconia implants compared with titanium: an in vivo study*. **Head Face Med**. 2008, 4,30. doi: 10.1186/1746-160X-4-30
12. Muddugangadhar BC, Amarnath GS, Tripathi S, Divya SD. *Biomaterials for Dental Implants: An Overview*. **International Journal of Oral Implantology and Clinical Research**. 2011. 2,13–24.
13. Chaturvedi TP. *An overview of the corrosion aspect of dental implants (titanium and its alloys)* **Indian J Dent Res**. 2009. 20,91–98. doi: 10.4103/0970-9290.49068
14. Manivasagam G, Dhinasekaran D, Rajamanickam A. *Biomedical Implants: Corrosion and its Prevention - A Review*. **Recent Patents on Corrosion Science**. 2010. 2,40–54
15. Adya N, Alam M, Ravindranath T, Mubeen A, Saluja B. *Corrosion in titanium dental implants: literature review*. **Journal of Indian Prosthodontic Society**. 2005. 5,126–131
16. Huebsch N, Mooney DJ. *Inspiration and application in the evolution of biomaterials*. **Nature**. 2009. 462,426–432. doi: 10.1038/nature08601
17. Rahmitasari F, Ishida Y, Kurahashi K, Matsuda T, Watanabe M, Ichikawa T. *PEEK with Reinforced Materials and Modifications for Dental Implant Applications*. **Dent J (Basel).** 2017. 5,4,35. doi: 10.3390/dj5040035.
18. Moharil S, Reche A, Durge K. *Polyetheretherketone (PEEK) as a Biomaterial: An Overview*. **Cureus**. 2023. 15,8,e44307. doi: 10.7759/cureus.44307
19. Ayyadanveettil P, Thavakkara V, Latha N, Pavanan M, Saraswathy A, Kuruniyan MS. *Randomized clinical trial of zirconia and polyetheretherketone implant abutments for single-tooth implant restorations: A 5-year evaluation*. **J Prosthet Dent**. 2022. 128,6,1275-1281. doi: 10.1016/j.prosdent.2021.02.037
20. Özkurt Z, Kazazoğlu E. *Zirconia dental implants: a literature review*. **J Oral Implantol**. 2011. 37,367–376. doi: 10.1563/AAID-JOI-D-09-00079

21. Kohal RJ, Weng D, Bächle M, Strub JR. *Loaded custom-made zirconia and titanium implants show similar osseointegration: an animal experiment*. **J Periodontol**. 2004. 75,1262-1268. doi: 10.1902/jop.2004.75.9.1262