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(REVIEW ARTICLE)

Current Updates in Implant Dentistry Materials

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Abstract

Background: Permanent tooth loss without replacement results in impaired chewing function, aesthetics, phonetics, and balance of the masticatory organs which can lead to more complex dental and oral health problems. Dental implants are the best treatment alternative today to restore masticatory function, aesthetics, and phonetics more perfectly. The use of implants allows tooth replacement that resembles the patient's previous natural teeth, both in terms of aesthetics and comfort. Until now, many types of materials have been studied and applied as dental implant materials.

Objective: This review aims to analyze the latest developments regarding materials used for dental implants.

Methods: A literature search was conducted on the PubMed, ScienceDirect, Cochrane, and Scopus databases until December 2023 using predetermined keywords and the results were limited to articles published in 2018-2023 with full-text open-access.

Conclusion: The selection of ideal implant material for patients can be adjusted to the patient's needs taking into account the physical, mechanical, and biocompatibility properties of the material.

Keywords: Dental Implants; Titanium; PEEK; Zirconia; Good Health and Well Being.

1. Introduction

One of the problems in the field of dental and oral health is tooth loss. Loss of permanent teeth in adults without replacing the missing teeth can impair chewing, aesthetic, and phonetic functions. In addition, there can be disturbances in the balance of the masticatory organs in the mouth, such as migration of neighboring teeth, extrusion of antagonist's teeth, loss of contact, caries, gingival recession, and periodontal pockets which result in more complex dental and oral health problems (1). Replacement of missing teeth can be done with the application of partial or complete removable dentures, fixed dentures, and dental implants. Along with the needs and desires of patients and the development of technology in dentistry, dental implants are the best alternative today to restore masticatory, aesthetic, and phonetic functions. Dental implants allow the replacement of teeth to resemble the patient's original teeth, both in terms of aesthetics and comfort (2).

An implant is a medical device made of one or more biomaterials, which is intentionally placed into the body and protected by body tissue. A dental implant is a component to replace missing teeth that is implanted in the jawbone or

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to support dental prostheses such as crowns, bridges, or dentures (1). For more than 30 years, dental implants have been widely used not only for the need to replace missing teeth but also for other dental treatments (2).

Implant materials commonly used in dentistry are titanium alloys. The most commonly used titanium alloys in the medical field are Ti-6Al-4V and α+β types. These alloys show good strength and biocompatibility. However, the appearance of metals is less aesthetic, causing non-metallic dental materials such as ceramics and polymers to be increasingly developed (2). The ceramic material commonly used for implants is zirconia. Zirconia-based implants are gaining more attention because of their unique characteristics, namely having a white color (better aesthetics), reducing bacterial affinity, having high flexural strength, and having the same osseointegration capacity as titanium (1,3). In addition, polymer materials such as polyetheretherketone (PEEK) are also widely discussed as dental implant materials. PEEK is a material that has high biocompatibility, good mechanical properties, high-temperature resistance, chemical stability, good wear resistance, and high bond strength with coating composites and luting cements (4,5). Therefore, this review article aims to review the latest developments in implant materials in dentistry.

2. Methods

This article focuses on discussing the latest developments in dental implant materials. A search was conducted in PubMed, ScienceDirect, Cochrane, and Scopus databases applying Boolean operator strategy, to identify eligible articles. A literature search in the period of August - December 2023 was conducted, for articles written in English, limited to publications within the last five years, and with full-text open-access. The search strategy included the following terms: ("titanium" OR "metallic" OR "titanium alloy") AND ("dental implant"), ("zirconium" OR "zirconia" OR "zirconium oxide") AND ("dental implant"), ("PEEK" OR "polyetheretherketone") AND ("dental implant").

The inclusion criteria for this literature study include: (a) articles explaining the composition and characteristics of implant materials in the form of titanium, zirconia, and PEEK, (b) types of original research studies, (c) articles published in the 2018-2023 period. Exclusion criteria included: (a) articles published not in the 2018 – 2023 time frame, (b) case report and review article types, (c) articles with full text that were not open access, and (d) articles that were not published in English.

3. Result

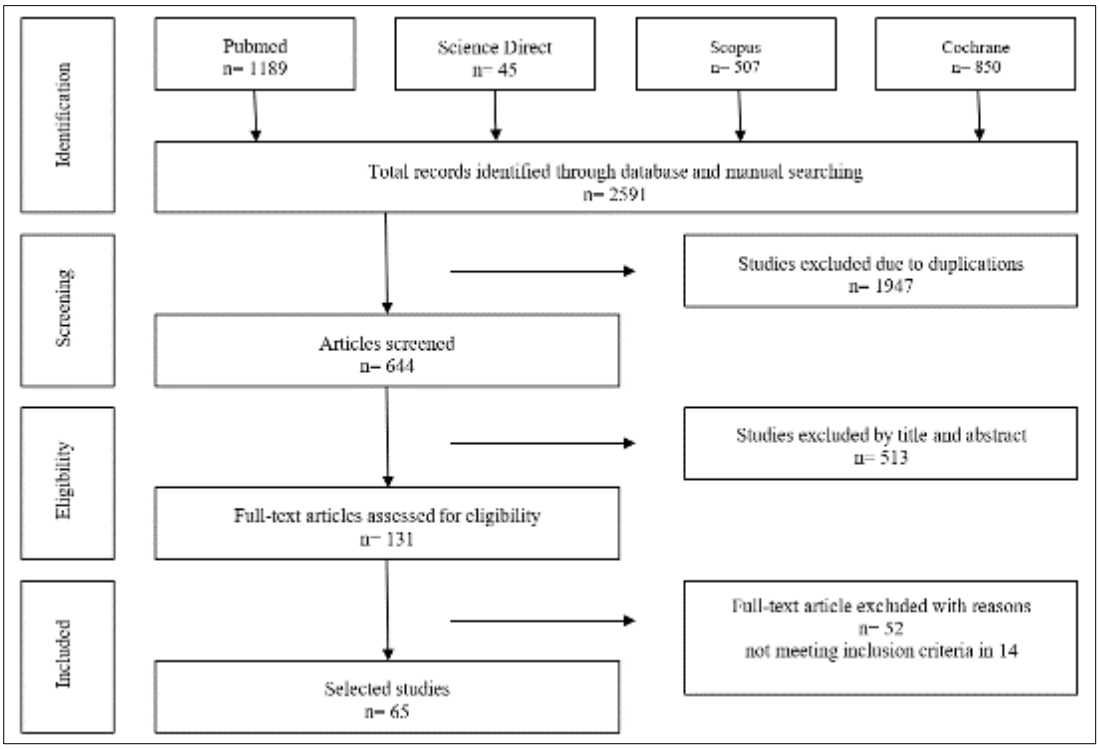

Figure 1 Flow chart and selection process of the included publications.

The search strategy revealed 2591 articles. After the removal of journals with the same title, 644 articles remained. Based on the study title and abstract, 513 articles were removed. After evaluating the remaining articles against the

eligibility criteria, a total of 65 articles were concluded in this review. The article selection process can be seen in Figure 1, while the included articles can be seen in Table 1.

Table 1 Primary outcomes of the included studies

Implant Materials	Title	Author	Journal	Primary Outcomes
Titanium	Zirconia versus titanium in dentistry	Hanawa, T. 2020	Dental Materials Journal	Ti-6Al-4V is easy to use and has heat-resistant properties, so it is widely used in the medical field.
	Bio-Tribocorrosion of Titanium Dental Implants and Its Toxicological Implications	Gaur, S. 2022	Scientific World Journal	Titanium grade V (Ti6Al4V) alloy is the type of titanium alloy that is most susceptible to tribocorrosion (material degradation process due to the combined effects of corrosion and wear).
	Emerging titanium surface modifications: The war against polymicrobial infections on dental implants	Baro, V. 2022	Brazilian Dental Journal	Titanium material shows a high percentage of treatment success and durability.
	Titanium Wear of Dental Implants from Placement, under Loading and Maintenance Protocols	Romanos, G. 2021	International Journal of Molecular Science	Titanium implant materials show good long-term treatment success.
	Stress distribution and failure analysis comparison between Zirconia and Titanium dental implants	Milone, D. 2022	Italian Biomedical and Dental Science Journal	The use of zirconia can improve the osseointegration process and long-term implant durability.
	Green synthesis and characterization of zirconium nanoparticles for dental implant applications	Chowdhury, M.. 2022	Bangladesh Mechanical Engineering Journal	Zirconia has corrosion resistance identical to titanium but with minimal negative effects.
	Advances of plant and biomass-extracted zirconium nanoparticles in dental implant applications	Hossain, N. 2023		Zirconia exhibits low affinity for plaque, tooth-like color, and good biocompatibility.
	Random, aligned and grassy: Bioactivity and biofilm analysis of Zirconia nanostructures as dental implant modification	Chopra, D. 2023	Composites Part B: Engineering	Zr-based dental implants show better aesthetic aspects and corrosion resistance than Titanium.
	Advancing dental implants: Bioactive and therapeutic modifications of zirconia	Chopra, D. 2021	Bioactive Materials Journal	ZrO2 exhibits good properties, such as esthetics; reduced affinity for bacterial plaque, reduced inflammatory infiltrate, and favorable soft tissue integration; reduced thermal conductivity, high flexural strength, and high fracture toughness; does not interfere with standard

				diagnostic techniques, such as *Magnetic Resonance Imaging* (MRI).
	Effect of restoration material on marginal bone resorption around modified anatomic zirconia dental implants: A randomized controlled trial	Aldebes, A. 2022	Annals of Medicine and Surgery	Zirconia can be an alternative to titanium implants which can show dark and unfavorable color on soft tissues (causing peri-implantitis).
	Is titanium–zirconium alloy a better alternative to pure titanium for oral implants? Composition, mechanical properties, and microstructure analysis	Sharma, A. 2020	Saudi Dental Journal	Titanium is widely accepted as a biomaterial for orthopedic and dental implants, due to its capacity to integrate directly into bone and its superior corrosion resistance.
	Mechanical stability of fully personalized, abutment-free zirconia implant crowns on a novel implant-crown interface	Hjerppe, J. 2022	Journal of Dentistry	Zirconia has been reported to have a high 5-year survival rate similar to metal-ceramic reconstructions but is more susceptible to abutment fracture compared to metal abutments.
	Mechanism of zirconia microgroove surface structure for osseointegration	Sun, Y. 2021	Today's advanced materials	Zirconia implants have osseointegration capabilities like titanium and have lower bacterial adhesion.
	Rehabilitation of edentulous jaws with zirconia complete-arch fixed implant-supported prostheses: An up to 4-year retrospective clinical study	Tischler, M. 2018	The Journal of Prosthetic Dentistry	Zirconia has aesthetic aspects for teeth and gums, strength, durability, and better biocompatibility compared to metal alloys.
	Long-term survival and success of zirconia screw-retained implant-supported prostheses for up to 12 years: A retrospective multicenter study	Pozzi, A. 2021		Zirconia has better biocompatibility than gold casting alloy with low bacterial surface affinity, good flexural strength, and does not cause discoloration of the mucosa.
	Clinical esthetic comparison between monolithic high-translucency multilayer zirconia and traditional veneered zirconia for single implant restoration in maxillary esthetic areas: Prosthetic and patient-centered outcomes	Zhang, C. 2022	Journal of Dental Science	Ceramic materials such as Zirconia are widely used because of their excellent mechanical and aesthetic properties
	Titanium–tissue interface reaction and its control with surface treatment	Hanawa, T. 2019	Frontiers in bioengineering and biotechnology	Pure titanium (CP Ti) and Ti alloys (Ti-6Al-4V) have good corrosion resistance, strength, and biocompatibility.
	Treatments for enhancing the biocompatibility of titanium implants	Stepanovska, J. 2020	Biomedical Papers of the Medical	Titanium implants exhibit good wear resistance, biocompatibility, and

			Faculty of Palacky University	corrosion resistance, and can integrate with bone rapidly.
	Titanium and titanium alloys in dentistry: Current trends, recent developments, and prospects	Hoque, ME 2022	Biomedical Papers of the Biomedical Engineering of Dhaka University	Titanium exhibits very high corrosion resistance in physiological fluids even when in contact with the surrounding environment.
	Surface characteristics and biocompatibility of cranioplasty titanium implants following different surface treatments	Hatamleh, M. 2018	Dental Materials Journal	The surface and mechanical properties of titanium implants are determined by the manufacturing method and surface treatment which greatly affect the repair of the defect area.
	Formation of carbon-added anatase-rich TiO2 layers on titanium and their antibacterial properties in visible light	Ueda, T. 2020		The formation of TiO2 layers shows an increase in the bond strength of the implant material as well as its antibacterial properties.
	Race to invade: Understanding soft tissue integration at the transmucosal region of titanium dental implants	Guo, T. 2021		The use of Ti as an implant material has shown poor epithelial attachment results and a lack of integration with the surrounding bone tissue.
	Analysis of bone stress and primary stability of a dental implant using strain and torque measurements	Nascimento, RXC 2023	Saudi Dental Journal	Implant failure is caused by low bone density, inadequate surgical procedures, bacterial contamination, previous periodontal infection, implant shape, and lack of primary stability due to low insertion torque.
	Dental implant surface morphology, chemical composition, and topography following double wavelength (2780/940 nm) laser irradiation. An in vitro study	Fahlstedt, P. 2023	Clinical and Experimental Dental Research	Titanium has adverse effects and causes increased expression of proinflammatory cytokines (TNF-a, IL-1, IL-6) in surrounding tissues.
	Biofilm accumulation on additive-manufactured Ti-6Al-4V alloy surface	Mari, K. 2022	Journal of Oral Science	Ti-6Al-4V alloy has excellent physical strength characteristics.
Zirconia	Zirconia Based Dental Biomaterials: Structure, Mechanical Properties, Biocompatibility, Surface Modification, and Application as Implant	Lin, H. 2021	Journal Frontiers in Dental Medicine	The biocompatibility of ZrO2 has been proven in both in vivo and in vitro tests, with no adverse reactions to cells and tissues. Advances in manufacturing technology and surface modification can improve the biosafety of ZrO2, supporting its use as a dental implant.

	Zirconia surface modifications for implant dentistry	Schunemann, FH. 2020	Materials Science and Engineering Journal	Modified zirconia surfaces show faster osseointegration than untreated ones, but there is no agreement regarding the optimal treatment method and morphological aspects.
	Classification and Properties of Dental Zirconia as Implant Fixtures and Superstructures	Ban, S. 2021	Dental Materials Science, School of Dentistry, Aichi Gakuin University Journal	The biocompatibility of ZrO2 has been proven to be good, and recent technologies may improve its safety as a dental implant.
	Advancing dental implants: Bioactive and therapeutic modifications of zirconia	Chopra, D. 2021	Bioactive Materials Journal	Zirconia implants and abutments are gaining popularity due to their esthetics, low bacterial affinity, and mechanical strength, with osseointegration capabilities equivalent to titanium.
	Zirconia in dental prosthetics	Greek, 2019	Journal of Materials Research and Technology	The implant stem is generally made of titanium for thread precision, but the abutment material is chosen for aesthetics. Ceramic abutments are gaining popularity due to their translucent properties.
	Advances of plant and biomass-extracted zirconium nanoparticles in dental implant applications	Hossain, N. 2023	Mechanical Engineering, IUBAT-International University of Business Agriculture and Technology Journal	Zirconia implants are becoming more common, but have not yet become the standard due to a lack of mechanistic and scientific research. Claims that nano-ZrO2 has antioxidant and anticarcinogenic properties are promising, but the potential toxicity of nanoparticles is still under investigation.
	A review of surface topographical modification strategies of 3Y-TZP: Effect in the physicochemical properties, microstructure, mechanical reliability, and biological response	Albeniz, N. 2023	Journal of the European Ceramic Society	The popularity of zirconia implants is increasing due to their superior mechanical properties, superior esthetics, and high biocompatibility. However, premature failure due to incomplete osseointegration remains a major problem.
	A review in titanium-zirconium binary alloy for use in dental implants: Is there an ideal Ti-Zr composing ratio?	Zhao, Q. 2023	Japanese Dental Science Review	Biocompatibility of dental implants is important to avoid toxic and inflammatory reactions. Released ions, such as Ti ions, can cause peri-implant mucositis and progress to peri-implantitis with bone resorption.

	Comparison of Cemented vs Screw-Retained, Customized Computer-Aided Design/Computer-Assisted Manufacture Zirconia Abutments for Esthetically Located Single-Tooth Implants: A 10-Year Randomized Prospective Study.	Amorfini, L. 2019	International Journal of Prosthodontics	Zirconia is increasingly being considered as an alternative to titanium due to its biocompatibility and aesthetic demands. Although considered a ceramic, zirconia is a metal oxide with ceramic properties and is often doped to meet specific needs.
	Randomized clinical trial of zirconia and polyetheretherketone implant abutments for single-tooth implant restorations: A 5-year evaluation. The Journal of Prosthetic Dentistry	Ayyadanveettil, P. 2022	The Journal of Prosthetic Dentistry.	Zirconia implant abutments have good strength and esthetics, with survival, biologic, and esthetic outcomes similar to titanium, although fracture strength can decrease by up to 50% after 10 years.
	Zirconia Dental Implants: A Closer Look at Surface Condition and Intrinsic Composition by SEM-EDX	Tchinda, A. 2023	Institut Jean Lamour, Université de Lorraine, Faculty of Science, Department of Micro and Nanomechanics for Life Journal	Zirconia implants are made of zirconium dioxide stabilized with yttrium and often alumina is added to increase the strength and properties of the implant.
	Classification and Properties of Dental Zirconia as Implant Fixtures and Superstructures.	Ban, S. 2021		The first application of zirconia in dentistry was 3Y-TZP, which has high strength but low translucency, used as a core for capping ceramics. TZP (3Y) with high translucency was developed by reducing alumina, allowing the formation of full zirconia crowns without capping ceramics and the color can be adjusted.
	13-year follow-up of a randomized controlled study on zirconia and titanium abutments	Hmm, VL 2023	Clinical Oral Implant Research	Clinicians must select implant restoration materials and types that are biocompatible, esthetic, and able to withstand physical forces, to ensure the success of the restoration.
	Evaluation of one-piece zirconia dental implants: An 8-year follow-up study	Kiechle, S. 2023	Clinical Oral Investigation	Zirconia dental implants showed high biocompatibility and low plaque adhesion. The study found that the success and survival rate of immediate zirconia implants reached 100%, while delayed implants reached 89.6% after 8 years.
	Immediate placement of one-piece zirconia implants with or without xenograft into the buccal gap. Soft tissues as secondary	Alves, D. 2023	Clinical Oral Implant Research	Zirconia implants have been shown to have similar survival rates to titanium implants in single-unit restorations and three-unit fixed dental

	outcomes of an experimental in vivo study			prostheses in the medium-term period.
	Influence of loading and aging on the fracture strength of an injection-molded two-piece zirconia implant restored with a zirconia abutment	Koha, R. 2022		The use of zirconium dioxide (ZrO2, zirconia), especially in the form of 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP), increases the fracture strength of ceramic implants and osseointegration is reported to be equivalent to titanium implants.
	Success and survival rates of immediate anatomical zirconia implants: a prospective clinical and radiographic evaluation	Al-Moziek. 2023	Brazilian Journal Oral Science	Dental implants are the best choice for replacing missing teeth due to their high success rate (90-100%). With the advancement of materials and surface treatment methods, this period has become shorter, and today implants can be placed 2-3 months after extraction, known as early implant placement.
	Evaluation of stress and deformation in bone with titanium, CFR-PEEK, and zirconia ceramic implants by finite element analysis	Mahalakshmi, G. 2023	Dental Research Journal	Zirconia ceramic implants are gaining popularity over metal implants because they are considered inert to the body, have good mechanical properties and better esthetics. The osseointegration of zirconia is similar to that of titanium.
	Long-term survival and success of zirconia screw-retained implant-supported prostheses for up to 12 years: A retrospective multicenter study	Pozzi, A. 2023	The Journal of Prosthetic Dentistry	Zirconia offers biocompatibility, high flexural strength, and superior esthetics compared to casting gold alloys, but its adoption is limited by the need for accurate impressions, difficult adjustments, and the risk of fracture and breakage of the covering ceramic.
	Success and patient satisfaction of immediately loaded zirconia implants with fixed restorations one year after loading	Rutkowski, R. 2023	Department of Oral and Maxillofacial Surgery, University Medical Center Hamburg-Eppendorf Journal	Implants made of zirconium dioxide may be superior to titanium implants in terms of bacterial adhesion and may reduce inflammatory mediators in the peri-implant tissue, resulting in better aesthetic results.
	Finite Element Analysis of Zirconia Dental Implants	Fiorillo, L. 2023	Department of Biomedical and Dental Sciences, Morphological and	Zirconia endosseous components, which are highly biocompatible and have high biomechanical performance, are used in orthopedic prostheses. They also have

			Functional Images, University of Messina Journal	advantages such as less plaque formation and better esthetics.
	Histologic and histomorphometric evaluation of new zirconia-based ceramic dental implants: A preclinical study in dogs	Chacun, D. 2021	Dental Materials Journal	Interest in ceramic implants is increasing due to improved aesthetics, with 3Y-TZP being chosen for its high corrosion resistance and superior mechanical properties associated with phase transformation toughening.
	Immunohistological composition of peri-implantitis affected tissue around ceramic implants—A pilot study	Fretwurst, T. 2021	Journal of Periodontology	This study showed that peri-implantitis lesions in ceramic and titanium implants had similar histological appearance, with plasma cells (CD138) and T lymphocytes (CD3) as the most predominant cells.
Polyether-Ether-Ketone (PEEK)	Behavior of polyether-ether-ketone (PEEK) in prostheses on dental implants	Blanch-Martinez, N. 2021	Journal of Clinical and Experimental Dentistry	PEEK is a partially crystalline polymer that has been used in industry and introduced to biomedicine. Patented in 1981 and approved by the FDA in 1990, primarily for Orthopedics, Traumatology, and Neurosurgery.
	Polyetheretherketone Material in Dentistry	Parate, KP 2023		PEEK is a promising material for dental restorations due to its cosmetic properties.
	PEEK in Fixed Dental Prostheses: Application and Adhesion Improvement	Wang, B. 2022	Public Health Dentistry, Sharad Pawar Dental College Journal	PEEK is a promising alternative material for fixed dental prostheses.
	Improved Mechanical Properties and Bioactivity of Silicate-Based Bioceramics Reinforced Poly (ether-ether-ketone) Nanocomposites for Prosthetic Dental Implantology	Taymour, N. 2022	Department of Substitutive Dental Sciences, College of Dentistry Journal	PEEK has a very stable chemical structure, which has been progressively used for orthopedic and dental implants.
	The use of PEEK in digital prosthodontics	Papathanasiou, L. 2020	BMC Oral Health Journal	PEEK is a material with high biocompatibility, good mechanical properties, high-temperature resistance, chemical stability, polishability, wear resistance, low plaque affinity, and high bond strength with coating composites and luting cement.

	PEEK for Oral Applications: Recent Advances in Mechanical and Adhesive Properties	Luo, C. 2023	Department of Oral and Maxillofacial Surgery, College of Stomatology, Guangxi Medical University Journal	PEEK has good biocompatibility, high-temperature resistance (melting point 343 ◦ C), excellent fatigue properties, high strength, relatively low wear rate (0.9 ± 1.1 mm3/MC), corrosion and aging resistance, ease of processing, and color stability.
	PEEK versus titanium-coated PEEK cervical cages: fusion rate	Godlewski, B. 2022	Department of Orthopedics and Traumatology, Military Institute of Medicine, Warsaw, Poland Journal	PEEK has been universally accepted due to its good mechanical properties.
	New biomaterials for modern dentistry	Heboyan, A. 2023	BMC Oral Health	PEEK can be modified by adding functional monomers (pre-polymerization) or postpolymerization modification through chemical processes such as sulfonation, amination, and nitration.
	The Role of Polyether Ether Ketone (Peek) in Dentistry	Bathala. 2023	Journal of Medicine and Life	PEEK has some characteristics that can be detrimental, such as the possibility of deformation under pressure and a certain solubility in water and water absorption in the coating resin, so it may be difficult to adapt to humid environments such as the oral cavity.
	Evaluation of stress and strain on mandible caused using “All-on-Four” system from PEEK in hybrid prosthesis: finite-element analysis	Shash, YH 2023	Odontology Journal	PEEK has many advantages, including high thermal stability (melting point ~334–343°C), high strength, excellent fatigue and creep resistance, high erosion resistance, ease of fabrication and forming, excellent self-lubricity, compatibility with imaging techniques (invisible during CT and MRI scans), excellent sterilization performance, and in vivo and in vitro biocompatibility.
	Current surface modification strategies to improve the binding efficiency of emerging biomaterial polyetheretherketone (PEEK) with bone and soft tissue	Chen, T. 2023	Journal of Prosthodontic Research	Surface modification of PEEK can improve tissue integration of PEEK as an ideal implant material.

	Stress analysis in implants, abutments, and peripheral bones with different restorative crown and abutment materials: A three-dimensional finite element analysis study	Rani, S. 2023	Dental Research Journal	PEEK has an elastic modulus similar to bone so it can reduce the protective effect of pressure on bone.
	Evaluation of stress and deformation in bone with titanium, CFR-PEEK, and zirconia ceramic implants by finite element analysis	Mahalakshmi, G. 2023		PEEK is very light, biologically inert, resistant to high temperatures and hydrolysis, has good mechanical and electrical properties, a low modulus of elasticity comparable to bone, is hypoallergenic, has no metallic taste, excellent polishing properties, and low plaque affinity.
	Evaluation of the bioactivity of surface modified polyetheretherketone (PEEK) as an implant material: an in vitro study	Martin, A. 2020	Contemporary Clinical Dentistry Journal	PEEK has the best wear-resistant and high-temperature stability among polymers and shows good biocompatibility in vitro and in vivo.
	The use of PEEK in digital prosthodontics	Papathanasiou, L. 2020	BMC Oral Health	PEEK has a higher modulus of resilience than lithium disilicate, comparable to gold alloy, indicating a high ability to elastically absorb damaging fracture energy.
	Peek applications in restorative dentistry: A comprehensive review os uses, advantages and future prospects	Banerjee, M. 2024	International Journal of Applied Dental Sciences, 10(1)	PEEK exhibits outstanding qualities, including high fracture resistance and an ideal elastic modulus similar to human bone.
	Study on Polyether-ether-ketone (PEEK) dental implants, future alternatives to Titanium	Parekh, et al. 2022	International Conference on Advances in Mechanical Engineering	PEEK abutments have lower abutment pressure properties than other materials.

4. Discussion

Edentulous restoration in patients with dental implants is a scientifically accepted method and recommended therapy (28). Dental implants are the recommended option for tooth replacement. Implants can be installed as tooth replacements under certain conditions. such as, (i) when teeth are lost due to non-periodontal diseases, due to caries infection, or traumatic injury; (ii) tooth loss due to periodontal disease but the remaining teeth can be maintained; and (iii) complex dental treatment that requires replacement of missing teeth (11). Implants are usually made of titanium or titanium alloys because they are biocompatible. Recent studies have shown that titanium dental implants last for more than 20 years, regardless of the type, with long-term use in the mouth (2). Once inserted into the bone, osseointegration of the implant is expected to occur and is fundamental to long-term use. However, dental implants cannot be used for the treatment of periodontal disease (3).

The use of implants can be said to be successful if there is no visible bone damage of less than 1 mm in the periodontal tissue. If there is bone damage of more than 1 mm, it can cause failure of implant installation involving furcation in

periodontal tissue disease. Bone adaptation patterns and gingival epithelium attachment are the main requirements in the installation of dental implants that can maintain contact between the bone and the implant without damaging the supporting tissue layer. The use of titanium in implants has high corrosion resistance, thanks to the presence of a titanium dioxide (TiO2) layer that covers the metal surface. This TiO2 layer can achieve direct contact with the bone implant obtained by a combination of screw design, strong drilling of the implant installation into the alveolar bone (27).

4.1. Titanium

Pure titanium (CP Ti) and Ti alloys (Ti-6Al-4V) are the most conventional for medical use. CP Ti and Ti-6Al-4V exhibit good workability, heat treatability, and weldability, as well as corrosion resistance, strength, and biocompatibility (2). Titanium implants have become the standard in the medical world for various reconstructive and prosthetic procedures due to their biocompatibility, lightweight, and corrosion resistance. Titanium can integrate with bone through the process of osseointegration, where bone will grow directly on the implant surface without any fibrous tissue forming between the two, thus increasing the stability and success of the implant (37). In the context of orthopedic surgery, titanium is widely used for the fabrication of various types of implants such as plates, screws, and joint prostheses due to its ability to withstand high mechanical loads while maintaining sufficient ductility (38).

The use of titanium in medical implants is also supported by its anti-allergic properties, which makes it suitable for use in patients with a history of metal allergies (39). In addition, titanium has an excellent strength-to-weight ratio, which means that implants made from this material can provide the necessary mechanical strength without adding excessive load to the patient's body (40). In dentistry, titanium is also widely used for dental implants due to the material's ability to integrate effectively with the jawbone, thus ensuring the long-term stability of the installed prosthesis (41).

The biocompatibility of titanium is determined by the thin surface layer of titanium dioxide (TiO2), which can be weakened or disrupted, causing titanium corrosion (29). When implants are placed in edentulous areas, residual materials used, such as metals, metal ions, lubricants, and detergents, may be present. These elements can even change the properties of the bone surface if there are residual materials even in small amounts and can affect the body's response during the osseointegration process, causing the formation of undesirable tissue at the bone/implant interface (42).

Depending on the type and concentration of alloying elements used, titanium alloys are divided into three groups: α-type, α+β-type, and β-type alloys. There are many different alloys made, but the most common for medical use is the Ti-6Al-4V alloy. In addition to corrosion resistance, strength, and biocompatibility, this alloy also exhibits good wear and heat resistance (2). There are five classifications regarding the understanding of biocompatibility, namely: (1) a condition of not experiencing toxicity as an effect of the host's biological system, (2) the ability of the material to adapt to the immune response in a specific application, (3) comparing the results of the implant material response with the side effects of the host tissue response, (4) relating to the ability of the biomaterial to perform its function without causing local damage and systemic effects on the host, (5) the capacity of the implant prosthesis to adapt in the body which is correlated with the effect on hormones, cells and tissue without causing changes (44) Titanium is used as an implant because of its low density and, compared to other materials, has the mechanical modulus that best matches bone (45).

In several studies, the biocompatibility of titanium has been confirmed; studies on the ability to mimic the formation of calcium phosphate in simulated body fluids; examination of osteoblast activity and calcification; and histological and molecular-biological examination of titanium implanted in animals, including bone formation, mean bone contact, and bone bond strength (13). Titanium is implanted into the bone, causing the surrounding tissue to react to it at an early stage, and the bone bond strength is increased. Adhesion and proliferation of osteogenic cells due to surface roughness, degree of limitation, and other factors are important components that regulate the compatibility of hard tissues (46).

Titanium is a type of implant used for medical applications because it has the following advantages: Excellent biocompatibility due to its high corrosion resistance properties and an oxide layer that protects both soft and hard tissues of the oral cavity., Low specific gravity and high strength, can be used for a very long time, can withstand high temperatures, Osseointegration in nature, Non-toxic and non-allergenic, can be mixed with other metals. Titanium material also has disadvantages in use in medical applications: Unable to be colored, titanium has a gray color so it can interfere with aesthetics, especially in conditions of thin mucosa and unfavorable soft tissue conditions or gingival recess, Expensive costs, Paramagnetic, weak magnetic attraction bonds (2).

Clinical trials of titanium implants have shown that this material has a high long-term success rate, with success rates often exceeding 95% after 10 years of use. Titanium implants have been considered the "gold standard" in implantology due to their reliable ability to support osseointegration, which is a key process for successful implantation. A recent meta-analysis comparing titanium implants with alternatives such as zirconium also found that although zirconium can be used as a substitute, titanium still performs superiorly in terms of survival rates and clinical success (24,25).

4.2. Zirconia

Zirconia implants refer to zirconia-based materials used in dental implant restorations. Zirconia abutments are increasingly used in implant dentistry due to their esthetic properties, mechanical strength, and biocompatibility (11,48). These abutments are customized to meet the specific needs of the patient and are used to support single-tooth restorations on dental implants. Zirconia abutments can be used in both screw-fixed and bonded restorations, providing a versatile option for implant-supported prosthetics. The use of zirconia in implant dentistry has shown promising long-term results, with high success rates and minimal complications (12). Zirconia implant abutments offer an excellent combination of strength and esthetics (13). Previous studies have reported from randomized controlled clinical trials that zirconia abutments have similar survival, biological outcomes, and esthetics to titanium abutments. However, zirconia abutments have been reported to be susceptible to age-related physical deterioration, with studies reporting a 50% decrease in fracture strength in zirconia after 10 years of simulated aging in an aqueous environment (14).

Zirconia implants are typically made of yttrium-stabilized zirconia (YSZ), a ceramic material composed of zirconium dioxide (ZrO2) stabilized with yttrium oxide (Y2O3). The yttrium oxide content in YSZ can vary, and different types of zirconia implants may have different yttrium contents. The composition of zirconia implants may also include other additives such as alumina (Al2O3) to improve some of its properties. For example, some zirconia implants may contain relatively high levels of alumina (0.25–0.5% by weight) to increase strength. On the other hand, zirconia implants with relatively low alumina content (less than 0.05% by weight) are used to achieve high clarity. The composition of zirconia implants can also vary depending on the desired properties and applications. For example, there are different types of zirconia implants available, such as high-clarity zirconia (HTZ), high-strength partially stabilized zirconia (PSZ), and polychromatic multilayer zirconia. These different types of zirconia implants have varying compositions and characteristics (15,16).

The strongest dental ceramic on the market is 3% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZPs), known as ZrO2. Because ZrO2 has high strength, hardness, wear resistance, corrosion resistance, similar to the elastic modulus of steel and iron, similar coefficient of thermal expansion, and high fracture toughness and chemical properties, ZrO2 has been widely used in biomedicine, such as in biosensors, cancer treatment, and hip replacement. ZrO2 can also be used for dental crowns, posts, and implants. One of the trends in dental implants is the development of new ceramic-based implants to improve the ability of periodontal integration and long-term adhesion with surrounding tissues, such as osseointegration. Compared with other types of ceramics, yttrium-stabilized tetragonal zirconia (YTZ) has better fracture toughness and flexural strength, as well as excellent wear resistance, corrosion resistance, high-temperature resistance, oxidation resistance, and hydrophilic properties (17).

Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) provide stimulation of osteogenic cells during osseointegration in combination with unique mechanical characteristics such as high fracture toughness, fatigue resistance, high flexural strength, high corrosion resistance, and radiopacity, as well as higher affinity for bone tissue than most alternative biocompatible ceramics.[18,49] Different types of zirconia are widely used for the fabrication of dental implants, structures, and fixtures. Zirconia-alumina composites, such as ATZ and NanoZR, are adequate for implant fixtures because they have excellent mechanical strength although their esthetic properties are not adequate. On the other hand, yttria-stabilized zirconia has been used for implant superstructures because of its adequate esthetic properties (50,51).

The main reasons why zirconium is preferred over titanium as a dental implant material are its opaque white color, reduced thermal conductivity, high flexural strength, high fracture toughness, reduced affinity for bacterial plaque, reduced inflammatory infiltration, and good soft tissue integration, which means reduced risk of peri-implant diseases. Compared with other metals, such as stainless steel, CoCr alloys, and Ti alloys, ZrO2 is non-magnetic, which means it does not interfere with standard diagnostic techniques, such as magnetic resonance imaging (12,19).

Biocompatibility refers to a material that can perform its function properly in the body without causing adverse effects, toxic, poisonous, or allergenic. Biocompatibility in this case refers to the ability of a material to cause good clinical therapeutic effects when combined with tissues in the human body. Zirconia-based materials are believed to have a good response system to tissues. Current clinical developments bring zirconia for many different uses such as crowns,

bridges, and even implants. For evaluate Biocompatibility of zirconia has been studied about osteoblasts, fibroblasts, lymphocytes, monocytes, and macrophages (20,52).

zirconia powder on human umbilical vein endothelial cells (HUVEC) fibroblasts through indirect contact, researchers concluded that zirconia powder (ZrO2/Y2O3) did not cause toxicity to fibroblasts. Biocompatibility Test on Lymphocytes, Monocytes, and Macrophages using Zirconia powder and particles tested in vitro on different cell lines (human and murine) lymphocytes, monocytes, or macrophages did not indicate any high toxicity or inflammation (TNF-α quantification). Biocompatibility Test on Osteoblasts found that zirconia did not cause toxic effects on connective tissue, immunological system, or bone tissue (21,22)

Zirconia-based materials have been claimed as biomaterials with high chemical stability that can prevent the release of toxic products into the surrounding tissue. Zirconia can stimulate osteogenic cells during the osseointegration process and has good mechanical characteristics. Clinically, zirconia has several advantages compared to other implant materials, namely its white color with translucency resembling human teeth. Pink Esthetic Score and White Esthetic Score performed on zirconia implant materials show results that are far superior when compared to titanium materials and aesthetically appear more satisfying (13,23). In addition, the ceramic particle content in zirconia implant material causes a lower inflammatory response and bone resorption, which indicates the superior biocompatibility of zirconia (19).

4.3. Polyether Ether Ketone (PEEK)

The type of therapy used to replace missing teeth is dental implants. Polyetherketone (PEEK) is a ketone-based crystalline thermoplastic resin characterized by good chemical, thermal and mechanical stability. PEEK is used in dentistry for implants, crowns, fixed partial dentures, and removable partial dentures. PEEK is a derivative of PAEK (polyarylertherketone) which has stability at high temperatures reaching 300^{o}C and greater resistance than most other metals (2,5,6,7).

PEEK exhibits excellent mechanical properties making it an ideal material for use in dentistry. The rigid structure can easily transfer the loads exerted by the implant to the bone structure but can also cause bone resorption. PEEK can be used to fabricate abutments and prosthetics due to its high mechanical properties compared to metal-supported ceramics. In addition, PEEK material is suitable for patients who are allergic to metals or are susceptible to metallic tastes (9).

PEEK is a semicrystalline, polycyclic, sulfonated aromatic high-temperature thermoplastic polymer with a linear structure. PEEK belongs to the polyaryletherketone family. It is obtained by bonding ketone and ether functional groups between aryl rings. It is brown in color in its pure form. The ether-ether ketone monomer units polymerize through a step-growth-dialkylation reaction of bis-phenolates to form polyetheretherketones. The standard synthetic route for PEEK is through the reaction between 4,40-difluoro benzophenone and the disodium salt of hydroquinone in a polar solvent such as diphenyl sulfone 300 8C. Modification of PEEK is also possible by the addition of functionalized monomers (pre-polymerization) or post-polymerization modification through chemical processes such as sulfonation, amination, and nitration. They are produced in three viscosities - high, medium, and low - with the same formula (-C6 H4 -OC6 H4 -O-C6 H4 -CO-). PEEK gets its strength from the aromatic ring structure chain. It is highly inert which makes it resistant to chemical erosion (3,34) Knowing the various characteristic properties of the mechanism such as density resistance, strength, flexibility, and elastic modulus of PEEK is very important to determine the indications for its application as an implant material (4,54).

Research that has been done shows that the modulus of elasticity of PEEK is around 4,000 MPa, almost the same as the modulus of elasticity of human bone. Having a low modulus of elasticity similar to human bone is one of the advantages of PEEK material as a denture material where it will not cause abrasion on the antagonist's teeth as occurs in ceramic materials. Good PEEK polishing will reduce the adhesion of bacterial plaque, and increase adhesion with other coating materials so that its strength becomes better (33).

There were also no cracks in the PEEK material mixed with Zirconium and Chromium-Cobalt in an in vitro study conducted by Nazari et al. (2016) as a crown material by providing a maximum vertical load of up to 1200 Nw. PEEK is considered to have the potential to be quite safe compared to other denture materials given a maximum strength of 500 Nw. PEEK has superior fatigue resistance to repeated stress comparable to other alloy materials (53,54). Pure PEEK has low density resistance so its use is limited. Pure PEEK was used for a while as a denture material until another component called Zirconium Oxide was introduced. The disadvantages of PEEK material are the possibility of

deformation and its solubility to liquids such as water absorption in the coating resin in the humid environment of the mouth.

PEEK biocompatibility is supported by US FDA Drug and device master files. PEEK is a non-toxic material, making it safe for use in humans. In MRI examination results, this material minimizes artifact images due to its radiolucent nature. In addition, PEEK has rigid properties with flexural strength ranging from 140-170 mPa and is also lightweight so it is comfortable to use (54). This material is anti-allergic, does not produce a metallic taste, produces excellent polishing, has low plaque affinity, and has good wear resistance (53).

There are several advantages of PEEK including good stability, good strength, good aesthetics, lighter than other materials, non-metallic, non-toxic, low irritation and allergic reactions, acceptable to patients, easy and time-consuming manufacturing procedures, good thermal properties can also be accepted by the oral cavity, good for use for dental implants because it has a modulus of elasticity similar to human cortical bone which makes it an excellent alternative to titanium and other metals (8).

PEEK has some characteristics that can be detrimental, such as the possibility of deformation under pressure and certain solubility in water and water absorption of the coating resin, which will be detrimental because it will be difficult to adapt to a humid environment such as the oral cavity environment. PEEK also has poor aesthetics compared to ceramics. Although PEEK has been used as a pioneering material in spinal, orthopedic, and sports medicine, the use of PEEK polymer materials in dental practice has not yet gained momentum. This may be due to the small number of long-term clinical studies available on the use of PEEK in clinical dental practice. Therefore, further research is needed on PEEK polymers as alternative materials to replace metals that have been used for a long time (3).

5. Conclusion

Many types of materials have been researched and developed for use as dental implant materials. Titanium, Zirconia, and PEEK materials are the right choices for use as dental implant materials because of their advantages in protecting bone structures, and have good biocompatibility, mechanical properties, and osseointegrity capabilities.

Compliance with ethical standards

Disclosure of Conflict of interest

No Conflict of interest to be disclosed.

References

[1] Hanawa T. Titanium–tissue interface reaction and its control with surface treatment. Front Bioeng Biotechnol. 2019 July 17;7:170.

[2] Heboyan A, Zafar MS, Rokaya D, Khurshid Z. Insights and Advancements in Biomaterials for Prosthodontics and Implant Dentistry. Molecules. 2022;27(5116):1-4. doi: 10.3390/molecules27165116.

[3] Papathanasiou I, Kamposiora P, Papavasiliou G, Ferrari M. The use of PEEK in digital prosthodontics. BMC Oral Health. 2020;20(217):1-11. doi: 10.1186/s12903-020-01202-7.

[4] Parate KP, Naranje N, Vishnani R, Paul P. Polyetheretherketone Material in Dentistry. Cureus. 2023;15(10):e46485. Published 2023 Oct 4. doi:10.7759/cureus.46485

[5] Stepanovska J, Matejka R, Rosina J, Bacakova L, Kolarova H. Treatments for enhancing the biocompatibility of titanium implants. Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub. 2020;164(1):23-33. doi:10.5507/bp.2019.062

[6] Taymour N, Fahmy AE, Gepreel MAH, Kandil S, El-Fattah AA. Improved Mechanical Properties and Bioactivity of Silicate Based Bioceramics Reinforced Poly(ether-ether-ketone) Nanocomposites for Prosthetic Dental Implantology. Polymers. 2021;14(1632):1-16. doi: 10.3390/polym14081632.

[7] Wang B, Huang M, Dang P, Xie J, Zhang X, Yan X. PEEK in Fixed Dental Prostheses: Application and Adhesion Improvement. Polymers (Basel). 2022;14(12):2323. Published 2022 Jun 8. doi:10.3390/polym14122323

[8] Banerjee M. Peek applications in restorative dentistry: A comprehensive review of uses, advantages and future prospects. Int J Appl Dent Sci. 2024;10(1):105-111. doi: 10.22271/oral.2024.v10.i1b.1900.

[9] Parekh A. Study on Polyether-ether-ketone (PEEK) dental implant, future alternatives to Titanium. IOP Conf. Ser.: Mater. Sci. Eng. 2022;1259:012045. doi: 10.1088/1757-899X/1259/1/012045.

[10] Chowdhury MA, Hossain N, Mostofa MG, et al. Green synthesis and characterization of zirconium nanoparticlefor dental implant applications. Heliyon. 2022;9(1):e12711. Published 2022 Dec 30. doi:10.1016/j.heliyon.2022.e12711

[11] Hossain N, Mobarak MH, Hossain A, Khan F, Mim JJ, Chowdhury MA. Advances of plant and biomass extracted zirconium nanoparticles in dental implant application. Heliyon. 2023;9(5):e15973. Published 2023 May 6. doi:10.1016/j.heliyon.2023.e15973

[12] Chopra D, Jayasree A, Guo T, Gulati K, Ivanovski S. Random, aligned and grassy: Bioactivity and biofilm analysis of Zirconia nanostructures as dental implant modification. Compos Part B Eng. 2023;259:110725. doi: 10.1016/j.compositesb.2023.110725.

[13] Gross C, Bergfeldt T, Fretwurst T, Rothweiler R, Nelson K, Stricker A. Elemental analysis of commercial zirconia dental implants - Is "metal-free" devoid of metals? J Mech Behav Biomed Mater. 2020;107:103579. doi: 10.1016/j.jmbbm.2020.103759.

[14] Tischler M, Patch C, Bidra AS. Rehabilitation of edentulous jaws with zirconia complete-arch fixed implant-supported prostheses: An up to 4-year retrospective clinical study. J Prosthet Dent. 2018;120(2):204-209. doi: 10.1016/j.prosdent.2017.12.010.

[15] Pozzi A, Arcuri L, Fabbri G, Singer G, Londono J. Long-term survival and success of zirconia screw-retained implant-supported prostheses for up to 12 years: A retrospective multicenter study. J Prosthet Dent. 2023;129(1):96-108. doi: 10.1016/j.prosdent.2021.04.026.

[16] Sun Y, Sun J, Wu X, Li Y, Li X, Li R, et al. Mechanism of zirconia microgroove surface structure for osseointegration. Mater Today Adv. 2021;12:100159. doi: 10.1016/j.mtadv.2021.100159.

[17] Schünemann FH, Galárraga-Vinueza ME, Magini R, Fredel M, Silva F, Souza JCM, Zhang Y, Henriques B. Zirconia surface modifications for implant dentistry. Mater Sci Eng C Mater Biol Appl. 2019;98:1294-1305. doi: 10.1016/j.msec.2019.01.062.

[18] Grech J, Antunes E. Zirconia in dental prosthetics: A literature review. J Mater Res Technol. 2019;8(5):4956-4964. doi: 10.1016/j.jmrt.2019.06.043.

[19] Zhao Q, Ueno T, Wakabayashi N. A review in titanium-zirconium binary alloy for use in dental implants: Is there an ideal Ti-Zr composing ratio? Jpn Dent Sci Rev. 2023;59:28-37. doi: 10.1016/j.jdsr.2023.01.002.

[20] Amorfini L, Storelli S, Mosca D, Scanferla M, Romeo E. Comparison of Cemented vs Screw-Retained, Customized Computer-Aided Design/Computer-Assisted Manufacture Zirconia Abutments for Esthetically Located Single-Tooth Implants: A 10-Year Randomized Prospective Study. Int J Prosthodont. 2018;31(4):359–366. doi:10.11607/ijp.5305

[21] Tchinda A, Lerebours A, Kouitat-Njiwa R, Bravetti P. Zirconia Dental Implants: A Closer Look at Surface Condition and Intrinsic Composition by SEM-EDX. Bioengineering (Basel). 2023;10(9):1102. Published 2023 Sep 20. doi:10.3390/bioengineering10091102

[22] Aldebes A, Al-Khanati NM, Abou Nassar J, Kharboutly NA, Aldamman F. Effect of restoration material on marginal bone resorption around modified anatomic zirconia dental implants: A randomised controlled trial. Ann Med Surg (Lond). 2022;80:104313. doi: 10.1016/j.amsu.2022.104313.

[23] Duan C, Ye L, Zhang M, et al. Clinical performance of zirconium implants compared to titanium implants: a systematic review and meta-analysis of randomized controlled trials. PeerJ. 2023;11:e15010. Published 2023 Mar 17. doi:10.7717/peerj.15010

[24] Fernandes PRE, Otero AIP, Fernandes JCH, Nassani LM, Castilho RM, de Oliveira Fernandes GV. Clinical Performance Comparing Titanium and Titanium-Zirconium or Zirconia Dental Implants: A Systematic Review of Randomized Controlled Trials. Dent J (Basel). 2022;10(5):83. Published 2022 May 12. doi:10.3390/dj10050083

[25] Gaur S, Agnihotri R, Albin S. Bio-Tribocorrosion of Titanium Dental Implants and Its Toxicological Implications: A Scoping Review. ScientificWorldJournal. 2022;2022:4498613. Published 2022 Oct 21. doi:10.1155/2022/4498613

[26] Barão VAR, Costa RC, Shibli JA, Bertolini M, Souza JGS. Emerging titanium surface modifications: The war against polymicrobial infections on dental implants. Braz Dent J. 2022;33(1):1-12. doi:10.1590/0103-6440202204860

[27] Romanos GE, Fischer GA, Delgado-Ruiz R. Titanium Wear of Dental Implants from Placement, under Loading and Maintenance Protocols. Int J Mol Sci. 2021;22(3):1067. Published 2021 Jan 21. doi:10.3390/ijms22031067

[28] Zhao Q, Ueno T, Wakabayashi N. A review in titanium-zirconium binary alloy for use in dental implants: Is there an ideal Ti-Zr composing ratio?. Jpn Dent Sci Rev. 2023;59:28-37. doi:10.1016/j.jdsr.2023.01.002

[29] Silveira SR, Sahm BD, Kreve S, Dos Reis AC. Osseointegration, antimicrobial capacity and cytotoxicity of implant materials coated with graphene compounds: A systematic review. Jpn Dent Sci Rev. 2023;59:303-311. doi:10.1016/j.jdsr.2023.08.005

[30] Msweli NP, Akinwamide SO, Olubambi PA, Obadele BA. Microstructure and biocorrosion studies of spark plasma sintered yttria stabilized zirconia reinforced Ti6Al7Nb alloy in Hanks' solution. Materials Chemistry and Physics. 2023;293:126940. doi:10.1016/j.matchemphys.2022.126940.

[31] Park JH, Olivares-Navarrete R, Baier RE, et al. Effect of cleaning and sterilization on titanium implant surface properties and cellular response. Acta Biomater. 2012;8(5):1966-1975. doi:10.1016/j.actbio.2011.11.026

[32] Godlewski B, Bebenek A, Dominiak M, Karpinski G, Cieslik P, Pawelczyk T. PEEK versus titanium-coated PEEK cervical cages: fusion rate. Acta Neurochir (Wien). 2022;164(6):1501-1507. doi:10.1007/s00701-022-05217-7

[33] Bathala L, Majeti V, Rachuri N, Singh N, Gedela S. The Role of Polyether Ether Ketone (Peek) in Dentistry - A Review. J Med Life. 2019;12(1):5-9. doi:10.25122/jml-2019-0003

[34] Nagi, N., Fouda, A.M. & Bourauel, C. Comparative evaluation of internal fit and marginal gap of endocrowns using lithium disilicate and polyether ether ketone materials - an in vitro study. BMC Oral Health 23, 207 (2023). https://doi.org/10.1186/s12903-023-02857-8

[35] Nishio F, Morita K, Doi K, et al. Radiopaque properties of polyetheretherketone crown at laboratory study. J Oral Biosci. 2023;65(3):253-258. doi:10.1016/j.job.2023.05.002

[36] Raghavendra S, Wood MC, Taylor TD. Osseointegration: A brief overview. J Prosthodont. 2005;14(4):265-273. doi:10.1111/j.1532-849X.2005.00052.x

[37] Geetha M, Singh AK, Asokamani R, Gogia AK. Ti based biomaterials, the ultimate choice for orthopaedic implants – A review. Progress in Materials Science. 2009;54(3):397-425. doi:10.1016/j.pmatsci.2008.06.004

[38] Sicilia A, Cuesta S, Coma G, Arregui I, Guisasola C, Ruiz E. Titanium allergy in dental implant patients: A clinical study on 1500 consecutive patients. Clin Oral Implants Res. 2008;19(8):823-835. doi:10.1111/j.1600-0501.2008.01544.x

[39] Milone, D., Fiorillo, L., Alberti, F., Cervino, G., Filardi, V., Pistonr, A., Cicciu, M & Risitano, G. Stress distribution and failure analysis comparison between Zirconia and Titanium dental implants: Italy Biomedical and Dental Science Journal. 2022;41: 680-691.

[40] Hoque ME, Showva NN, Ahmed M, et al. Titanium and titanium alloys in dentistry: current trends, recent developments, and future prospects [retracted in: Heliyon. 2024 May 27;10(11):e31978. doi: 10.1016/j.heliyon.2024.e31978]. Heliyon. 2022;8(11):e11300. Published 2022 Oct 28. doi:10.1016/j.heliyon.2022.e11300

[41] Hatamleh, MM., Wu, X., Alnazzawi, A., Watson, J & Watts, D. Surface characteristics and biocompatibility of cranioplasty titanium implants following different surface treatments. Elsevier. 2018; 34(4): 676-683.

[42] Ueda, T., Sato, N., Kizumi, R., Ueda, K., Ito, K., Ogasawara, K & Narushima, T. Formation of carbon-added anatase-rich TiO2 layers on titanium and their antibacterial properties in visible light. Dental Material Journal. 2021;37(2): 37-46.

[43] Nascimento, L.R.X.C., Torelly, GM., Elias, CN. Analysis of bone stress and primary stability of a dental implant using strain and torque measurements. Saudi Dental Journal. 2023; 35(3): 263-269.

[44] Fahlstedt, P., Wennerberg, A., Bunaes, DF., Lie, SA & Leknes, KN. Dental implant surface morphology, chemical composition, and topography following double wavelength (2780/940 nm) laser irradiation. An in vitro study. Clinical Exp Dental Res. 2023; 9(1): 25-35.

[45] Zhang, CN., Zhu, Y., Zhang, YJ & Jiang, YH. Clinical esthetic comparison between monolithic high-translucency multilayer zirconia and traditional veneered zirconia for single implant restoration in maxillary esthetic areas: Prosthetic and patient-centered outcomes. Journa of Dental Science. 2022;17(3): 1151-1159.

[46] Lin, H., Yin, C. & Mo, A. Zirconia Based Dental Biomaterials : Structure, Mechanical Properties, Biocompatibility, Surface Modification, and Application as Implant. Frontiers in Dental Medicine. 2021; 289198.

[47] Chacun, D., Lafon, A., Courtois, N., Reverson, H., Chevalier, J., Margossian, P., Alves, A., Gritsch, K & Grosgogear, B. Histologic and histomorphometric evaluation of new zirconia-based ceramic dental implants: A preclinical study in dogs. Journal of Dental Material. 2021; 37(9): 1377-1389.

[48] Ban S. Classification and Properties of Dental Zirconia as Implant Fixtures and Superstructures. Materials (Basel). 2021;14(17):4879. Published 2021 Aug 27. doi:10.3390/ma14174879

[49] Albeniz, NG., Pique, EJ., Roa, JJ & Moruno, CM. A review of surface topographical modification strategies of 3Y-TZP: Effect in the physicochemical properties, microstructure, mechanical reliability, and biological response. Journal of the European Ceramic Society. 2023; 43(8): 2977-3004.

[50] Martin A, Azhagarasan NS, Ravichandran M, Ramakrishnan H, Jaya Krishnakumar S, Mahadevan V. Evaluation of the Bioactivity of Surface Modified Polyetheretherketone (PEEK) as an Implant Material: An In Vitro Study. Contemp Clin Dent. 2020;11(4):356-366. doi:10.4103/ccd.ccd_258_19

[51] Luo C, Liu Y, Peng B, et al. PEEK for Oral Applications: Recent Advances in Mechanical and Adhesive Properties. Polymers (Basel). 2023;15(2):386. Published 2023 Jan 11. doi:10.3390/polym15020386

[52] Shash, YH., Wakad, MTE., Eldosoky, MAA & Dohiem, MM. Evaluation of stress and strain on the mandible caused using “All-on-Four” system from PEEK in hybrid prosthesis: finite-element analysis. Odontology. 2023; 111:618-629.

[53] Chen, T., Jinno, Y., Atsuka, I ., Tsuchiya, A., Stocchero, M., Bressan , E & Ayukawa, Y. Current surface modification strategies to improve the binding efficiency of emerging biomaterial polyetheretherketone (PEEK) with bone and soft tissue: A literature review. Journal Prosthodont Res. 2023; 67(3): 337-347.

[54] Mahalakshmi G, Gasthi A, Hosain Almansour HM, et al. Evaluation of stress and deformation in bone with titanium, CFR-PEEK and zirconia ceramic implants by finite element analysis. Dent Res J (Isfahan). 2023;20:57. Published 2023 May 26.