Advances in Polyetheretherketone (PEEK) Biomaterials in Dental Implantology: A Comprehensive Review

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***Abstract*—In dental implantology, polyetheretherketone (PEEK) is a noteworthy biomaterial because of its mechanical, biological, and aesthetic qualities. It is a semicrystalline thermoplastic that reduces stress shielding by imitating the elastic modulus of cortical bone. PEEK's tooth-colored appearance meets aesthetic criteria, and its radiolucency improves diagnostics. Additionally, it minimizes allergic reactions and provides outstanding fatigue strength, chemical resistance, and biocompatibility. Its hydrophobicity and bioinertness, however, make osseointegration difficult. Improved cellular adherence and antibacterial qualities are the results of surface modification procedures such as hydroxyapatite coatings and plasma treatments. PEEK composites bonded with carbon fiber increase strength without sacrificing their bone-like elastic modulus.**

PEEK's shock-absorbing qualities and low weight make it a popular choice for dental applications such implant abutments, prosthetic frames, and orthodontic devices. The literature on PEEK biomaterials is compiled in this review, which includes information on their characteristics, surface developments, therapeutic applications, and limits. In order to evaluate PEEK's efficacy in comparison to conventional materials, more clinical trials and long-term data are required. PEEK holds a lot of promise as a flexible, patient-friendly choice in implantology and prosthodontics, with the goal of enhancing implant durability, biocompatibility, and aesthetics, according to developments in surface modifications and hybrid composites.

I. INTRODUCTION

The field of dental implantology and prosthodontics continually seeks materials that optimally replicate the biomechanical, biological, and aesthetic qualities of natural teeth and supporting structures. Traditional metallic implants, particularly titanium and its alloys, have long served as the gold standard due to their excellent strength, corrosion resistance, and osseointegration capability. However, despite their overall success and longevity, titanium implants possess inherent limitations that have prompted ongoing research into alternative biomaterials.[1]

Additionally, titanium implants often present aesthetic challenges, particularly in anterior regions or in patients with thin mucosal biotypes, where metallic hue can cause unsightly darkening of peri-implant soft tissues, compromising smile aesthetics. Furthermore, titanium implants can complicate diagnostic imaging by causing artifacts in magnetic resonance imaging (MRI), and though rare, some patients experience allergic or hypersensitivity reactions to metal ions released through corrosion or wear.[4][5]

In response to these issues, polyetheretherketone (PEEK), a high-performance semicrystalline thermoplastic polymer, has garnered substantial attention as an alternative dental biomaterial. Originally developed for aerospace and medical engineering applications, PEEK exhibits an elastic modulus closely aligned with that of cortical bone, offering a more harmonious mechanical load transfer and reducing the risk of bone resorption due to stress shielding effects. Its favorable mechanical properties include excellent fatigue resistance, high fracture toughness, and resilience even under prolonged cyclic loading conditions, addressing the biomechanical demands of dental implant support.[7][10]

Beyond mechanics, PEEK is inherently biocompatible, demonstrating low cytotoxicity and minimal inflammatory or allergic reactions when in contact with oral tissues. Unlike metals, PEEK's tooth-colored translucency provides enhanced aesthetic integration in dental prostheses, particularly valuable for crowns, abutments, and removable prostheses in the esthetic zone. Additionally, PEEK's radiolucency facilitates post-treatment radiographic examinations without the artifact interference common with metallic implants.[8][11]

Despite these advantages, PEEK's bioinert surface and hydrophobic character limit its ability to promote direct bone apposition and osseointegration, posing a primary challenge for its use as a dental implant material. To overcome this, extensive research efforts focus on surface modification techniques, including plasma treatments, coatings with bioactive substances such as hydroxyapatite and titanium dioxide, and nanoscale texturing to enhance cellular adhesion, proliferation, and differentiation on the implant surface.[6][11]

Clinically, PEEK has been successfully applied in frameworks for fixed and removable prostheses, implant abutments, temporary implant components, and orthodontic appliances. Its shock-absorbing capabilities and lightweight nature contribute to patient comfort and reduced mechanical stress on surrounding bone and soft tissues. However, PEEK's developmental stage necessitates further long-term clinical studies to validate its performance as a definitive implant material.[8][9]

This review presents a comprehensive examination of PEEK's physical and biological properties, surface modification strategies, clinical applications, advantages, and limitations. It also outlines future prospects for PEEK in dental implantology and prosthodontics, emphasizing the critical role of interdisciplinary research in transforming PEEK from a promising polymer to a standard-of-care biomaterial.

II. MATERIAL PROPERTIES AND MECHANICAL CHARACTERISTICS

Polyetheretherketone (PEEK) is a high-performance semicrystalline thermoplastic polymer that stands out for its remarkable combination of mechanical strength, resilience, and stability, making it a highly attractive candidate for dental biomaterial applications. Its unique chemical structure, characterized by aromatic rings interconnected by ketone and ether groups, confers outstanding thermal stability, chemical resistance, and mechanical performance under demanding physiological conditions.[7]

Mechanical Strength and Elastic Modulus

One of the most significant advantages of PEEK in implantology is its elastic modulus, typically around 3.6 GPa in its pure form, which can be enhanced up to approximately 18 GPa when reinforced with carbon fibers (CFR-PEEK). This range approaches the elastic modulus of human cortical bone (~15–20 GPa), which is critical in providing biomechanical compatibility. In contrast to titanium alloys, whose elastic moduli are over 100 GPa, PEEK's bone-like flexibility markedly reduces stress shielding a phenomenon where excessive mechanical stress is borne by the implant rather than the surrounding bone, leading to peri-implant bone resorption and potential implant failure. Such biomechanical harmony allows for a more physiological load distribution during mastication and functional activities, promoting bone preservation around the implant site.[14]

Tensile Strength and Fracture Resistance

PEEK exhibits tensile strengths ranging from 80 to 120 MPa depending on the grade and reinforcing additives, sufficient for resisting functional masticatory loads in the oral cavity. CFR-PEEK composites demonstrate enhanced fracture toughness and fatigue resistance, which are paramount in enduring cyclic mastication without microcracks or catastrophic failures. Its inherent toughness also offers improved shock absorption capacity, protecting both the implant structure and the surrounding bone from impact forces and overload, unlike brittle ceramic materials or excessively stiff metals.[20]

Flexural Properties and Fatigue Behavior

The flexural modulus and strength of PEEK also align well with the demands of dental applications. Studies demonstrate its resistance to deformation under load, while cyclic fatigue testing confirms exceptional durability against repeated loading cycles simulating years of chewing forces. This endurance ensures prolonged mechanical integrity and reliability in both implant fixtures and prosthetic components fabricated from PEEK.[5][12]

Thermal And Chemical Stability

PEEK's thermal properties feature a high melting point of approximately 343°C and a glass transition temperature around 143°C, which imply excellent stability during sterilization processes and clinical handling. Its resistance to hydrolytic degradation and chemical attack from oral fluids, acids, and cleaning agents secures its functionality and longevity in the harsh oral environment. However, care must be taken during fabrication processes as its mechanical properties may degrade beyond temperatures of 250°C. [7][17]

Density And Weight Considerations

With a density near 1.3 g/cm³, PEEK is significantly lighter than titanium (density ~4.5 g/cm³) and zirconia ceramics, which contributes to increased patient comfort and reduced prosthesis weight. This lightness aids in minimizing stress on the underlying bone and soft tissues during function.[4][5]

Surface Characteristics and Modifications

Native PEEK has a relatively smooth and hydrophobic surface, which, while offering low plaque adherence, limits cellular adhesion essential for integration with hard and soft tissues. Mechanical roughening, plasma treatment, sulfonation, and bioactive coatings are routinely applied to enhance surface energy and roughness, thus improving osteoblast attachment and bone formation. Nanoparticle incorporation further alters mechanical and biological properties, enabling a multifunctional biomaterial customized for dental applications.[6][11]

Fabrication Versatility

The thermoplastic nature of PEEK allows it to be processed by various conventional techniques such as injection molding, extrusion, and compression molding, but it also lends itself exceptionally well to modern digital dentistry fabrication methods, including CAD/CAM milling and additive manufacturing. This versatility facilitates the production of complex custom prostheses, implant components, and precision-fit restorations, which is critical in contemporary implant prosthodontics.[13]

III. SURFACE MODIFICATION AND BIOACTIVITY ENHANCEMENT

Despite its favorable mechanical and physical properties, native polyetheretherketone (PEEK) presents significant challenges for dental implant applications due to its inherently bioinert and hydrophobic surface characteristics. These surface properties limit effective osseointegration the direct structural and functional connection between living bone and implant surface which is pivotal for implant stability and long-term success. Additionally, the hydrophobic nature of PEEK impedes protein adsorption and osteoblast attachment, while the lack of bioactive functional groups restricts interactions with surrounding tissues. Consequently, significant efforts in dental biomaterials research focus on surface modification strategies aimed at enhancing PEEK's bioactivity and promoting favorable biological responses.[16]

Surface Roughening And Physical Treatments

Mechanical surface roughening techniques such as sandblasting, acid etching, and laser texturing increase surface area and roughness, offering improved mechanical interlocking for bone growth and soft tissue adherence. Laser treatments can create nanoscale topographies mimicking natural bone surface architecture, which in turn enhances early cellular attachment and proliferation of osteoblasts. Similarly, plasma treatments modify surface chemistry and energy, converting the hydrophobic surface to a more hydrophilic one, thereby improving protein absorption and cell adhesion. Oxygen plasma treatments and argon plasma treatments are commonly employed to introduce polar functional groups that facilitate integrin binding on cells. [17] [19

Chemical And Sulfonation Treatments

Chemical modifications like sulfonation introduce negatively charged sulfonic acid groups (-SO3H) on the PEEK surface, increasing roughness and hydrophilicity. This treatment also facilitates functional group interaction with bone morphogenetic proteins (BMPs) and extracellular matrix molecules, promoting osteoinductive properties. Hydroxylation and amination techniques incorporate biologically active groups that improve cellular signaling pathways critical for bone regeneration.[15]

Bioactive Coatings

Coating PEEK surfaces with bioceramics such as hydroxyapatite (HA), bioactive glass, or calcium phosphate powders significantly improves osseointegration by providing a biomimetic interface that mimics the mineral phase of bone. Methods such as plasma spraying, dip-coating, electrophoretic deposition, and sputter coating securely apply these bioactive layers on PEEK surfaces. These coatings enhance osteoblast differentiation, mineralization, and calcium ion release, accelerating new bone formation around implant sites.[3][7]

Moreover, titanium dioxide (TiO2) coatings applied via plasma spraying or anodization create a biologically favorable surface with photocatalytic and antimicrobial properties, reducing bacterial colonization risks during the early healing phase. Nanostructured TiO2 surfaces further promote osteogenic activity and soft tissue sealing.[13]

Nanoparticle Incorporation and Functionalization

The inclusion of nanoparticles such as nano-hydroxyapatite, fluorohydroxyapatite, titanium dioxide, and zirconia within the PEEK matrix or as surface modifications provides multifunctional enhancements. Nanoparticles increase surface roughness and energy, improving cell-material interactions, while fluorohydroxyapatite imparts antibacterial properties, minimizing peri-implant infections. These nano-scale modifications closely regulate protein adsorption and cell behavior, critical to successful tissue integration.[7][14]

Functionalization with bioactive molecules, peptides (e.g., RGD sequences), and growth factors further endows the PEEK surface with tailored biological cues that stimulate osteogenesis, angiogenesis, and immunomodulation, leading to improved early healing and implant stability.[5]

IV. ANTIBACTERIAL SURFACE ENGINEERING

Bacterial colonization at the implant site remains a primary cause of implant failure. To address this, PEEK surfaces are modified with antimicrobial agents such as silver nanoparticles, chitosan coatings, zinc ions, and photocatalytic TiO2 nanoparticles, which prevent biofilm formation while maintaining biocompatibility. These coatings may either release antibacterial substances or create surfaces disruptive to bacterial adhesion, balancing antimicrobial efficacy with tissue integration.[12]

Summary of Biological Outcomes

Preclinical studies demonstrate that surface-modified PEEK implants achieve significantly higher bone-to-implant contact ratios, increased osteoblast activity, and enhanced biomechanical fixation compared to unmodified PEEK surfaces. These modifications stimulate accelerated bone remodeling and reduce bacterial colonization in vivo. However, the stability and durability of coatings under functional load and long-term intraoral conditions require extensive clinical evaluation.[19]

Future Trends

Emerging technologies such as layer-by-layer coatings, micro- and nano-fabricated surface patterns, and combination strategies integrating mechanical, chemical, and biological modifications are being explored. Advances in additive manufacturing also open opportunities for incorporating bioactive agents during 3D printing of PEEK implants, enabling patient-specific implants with customized surface bioactivity profiles.[14]

V. CLINICAL APPLICATIONS IN IMPLANTOLOGY

Polyetheretherketone (PEEK) has rapidly become a material of interest in the field of implant dentistry, with expanding applications from implant fixtures to abutments and prosthetic components. Its inherent mechanical compatibility, favorable biological profile, and aesthetic advantages underpin PEEK's potential to enhance implant success and patient satisfaction. This section comprehensively explores PEEK's role in various implant-related clinical applications, highlighting current evidence, material performance, benefits, and challenges.[20]

Implant Fixtures

Although titanium remains the conventional choice for dental implant fixtures due to its proven osseointegration and mechanical strength, PEEK and its composites—especially carbon fiber-reinforced PEEK (CFR-PEEK)—offer compelling benefits. PEEK implants exhibit an elastic modulus closer to natural bone, which mitigates stress shielding effects. This biomechanical congruence supports optimal load transfer and helps preserve peri-implant bone density, potentially extending implant longevity and reducing marginal bone loss risk.[20]

However, pure PEEK lacks sufficient intrinsic bioactivity and mechanical strength to serve as a standalone definitive implant material. Therefore, its current use as implant fixtures tends to be limited to provisional or short-term applications, or where metal allergies exist. Composite reinforcements and surface bioactivations seek to overcome these limitations. Early animal studies and limited clinical trials indicate promising bone-to-implant contact ratios and osseointegration potential for surface-modified PEEK implants, but long-term human data remain sparse.[14][16]

Abutments

PEEK abutments have gained popularity, particularly for their shock-absorbing properties due to modulus similarity to bone, which may reduce peri-implant bone stress and mechanical failures. They provide an attractive metal-free alternative, especially in patients with hypersensitivity to metals or aesthetic concerns in anterior regions. PEEK abutments avoid darkening of peri-implant mucosa and eliminate galvanic corrosion issues common with metallic abutments.[12]

Carbon fiber reinforced PEEK abutments demonstrate improved fracture resistance and structural integrity but generally do not match the ultimate strength of titanium abutments. Concerns persist over mechanical complications such as screw loosening or fracture, which require refined design and material formulations. However, PEEK's resilience makes retrieval easier in case of abutment screw failure, avoiding severe implant damage.[11][12]

Implant Screws and Prosthetic Components

PEEK implant screws and prosthetic components, reinforced with carbon fibers and engineered for bone-like elasticity, aim to reduce stress concentration points and mechanical wear within the implant system. While titanium screws maintain superior mechanical strength under torque and cyclic loading, PEEK screws provide favorable biomechanical flexibility and ease of removal in case of failure. Optimization of screw design, fiber orientation, and surface treatments is ongoing to balance strength with beneficial elastic properties.[14]

Prosthetic Frameworks and Crowns

PEEK's use extends to implant-supported prosthetic frameworks, crowns, bridges, and removable attachments. The polymer's aesthetic tooth-like color and translucency outperform metallic frameworks in patient acceptability, particularly when veneered with composite resins or ceramics. Its lightweight nature and shock absorption mitigate mechanical strain on implants and soft tissues, which is especially beneficial in high load or parafunctional patients.[4][9]
CAD/CAM technology allows precise fabrication of PEEK prosthetic components with excellent marginal fit and durability. Clinical studies report satisfactory fracture resistance and retention with PEEK-based implant-supported prostheses, although the material's wear resistance against natural teeth and definitive crown materials requires further evaluation.[9]

Soft Tissue Interaction and Osseointegration

PEEK abutments are reported to create favorable peri-implant soft tissue responses with minimal inflammation, possibly relating to reduced bacterial adhesion and surface biocompatibility. This contributes to improved mucosal sealing and potentially lower peri-implantitis rates. Modification of PEEK surfaces both on implant fixtures and abutments aims to further enhance osseointegration and epithelial attachment, mitigating biological complications.[2][9]

Limitations and Future Directions

Despite promising features, the widespread adoption of PEEK in implantology is hindered by limited long-term clinical data, mechanical property variations across formulations, and surface bioactivity challenges. Evolving approaches—such as nanocomposite reinforcements, bioactive coatings, and integration of antimicrobial agents—are under active investigation to address these issues. Large-scale clinical trials assessing survival rates, peri-implant bone stability, and prosthetic complications are crucial to validate PEEK's efficacy as a mainstream implant material.[5][8]Future Perspectives

Here is an elaborated and detailed section on Future Perspectives for the review article on PEEK in dental implants and prosthodontics:

Future Perspectives

The future of polyetheretherketone (PEEK) as a dental biomaterial is promising, buoyed by ongoing advancements in materials science, surface engineering, and digital manufacturing. While its unique mechanical compatibility with bone, aesthetic qualities, and biocompatibility offer significant advantages over traditional metallic and ceramic biomaterials, PEEK's broader clinical adoption as a definitive implant material and prosthetic component hinges on overcoming current challenges related to bioinertness, mechanical optimization, and evidence-based validation.[3][7][14]

VI. MULTIFUNCTIONAL SURFACE ENGINEERING

One of the foremost avenues for future development is the creation of multifunctional PEEK surfaces that simultaneously promote osteogenesis, inhibit bacterial colonization, and possess durable mechanical stability. Layer-by-layer coatings and nanostructured surface architectures integrating bioactive ceramics (e.g., hydroxyapatite, bioactive glass), antimicrobial ions (silver, zinc, copper), and growth factors can synergistically enhance early bone formation and reduce peri-implant infections. Advances in controlled release systems embedded on PEEK surfaces could provide sustained delivery of therapeutic agents, further improving clinical outcomes in challenging cases.[11][15]

Composite and Hybrid Biomaterials

Composite formulations blending PEEK with carbon fibers, nano-ceramics, or polymer blends aim to tailor mechanical properties such as elastic modulus, fracture toughness, and fatigue resistance to match patient-specific needs and anatomical variations. Hybrid biomaterials that combine PEEK with titanium or zirconia in layered or graded structures could offer advantageous combinations of strength, osseointegration, and aesthetics. Such designs may enable definitive PEEK-based implants with mechanical performance comparable to metals while maintaining superior biocompatibility and radiolucency.[16][20]

Advanced Fabrication and Additive Manufacturing

Emerging digital dentistry technologies, including high-precision CAD/CAM milling and additive manufacturing (3D printing), allow the fabrication of complex, patient-specific PEEK implants and prosthetics with optimized macro- and micro-architecture. Customized porous structures and lattice designs can mimic trabecular bone morphology, enhance vascularization, and improve biomechanical function. Additive manufacturing also facilitates the seamless incorporation of antimicrobial or osteoinductive agents during fabrication, accelerating development of next-generation smart implants.[11][13]

Clinical Translation and Long-Term Validation

Despite promising preclinical results, extensive clinical trials with long-term follow-up remain necessary to establish PEEK's safety, efficacy, and survival outcomes compared to established materials. Prospective randomized controlled trials evaluating peri-implant bone stability, soft tissue health, prosthetic complications, patient satisfaction, and economic considerations will be instrumental. These studies will elucidate ideal clinical indications, implant designs, and surface modification protocols for PEEK.[17]

Personalized and Precision Implantology

The integration of PEEK biomaterials with digital workflows, artificial intelligence, and patient-specific diagnostic data heralds a future of precision implantology. Customized PEEK implants tailored for individual biomechanical environments and genetic predispositions may optimize load distribution, osseointegration, and tissue response, reducing failure rates and enhancing patient outcomes.[4][20]

Sustainable and Biocompatible Material Development

PEEK's potential for biocompatible surface functionalization also aligns with the growing movement toward sustainable biomaterials in dentistry. Innovations focused on reducing environmental impact, recyclability, and non-toxic processing may further establish PEEK as an environmentally responsible choice in oral rehabilitation.[9][12]

VII. CONCLUSION

Here is an elaborated and detailed Conclusion section for the review article on PEEK in dental implants:
Polyetheretherketone (PEEK) has emerged as a transformative biomaterial with the potential to redefine dental implantology. In summary, PEEK represents a major step forward in dental biomaterials, offering a versatile platform that leverages its unique properties to overcome many limitations of existing materials. Its continued development and clinical validation will pave the way for improved implant survival, functional performance, and patient-centered care in the coming decade.

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