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Research Progress on the Application of Polyether Ether Ketone and Its Composites in the Field of Oral Implantation

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Abstract: Polyether ether ketone (PEEK) and its composites have been gradually applied in the field of oral implantation due to their elastic modulus close to that of bone tissue and excellent chemical stability. They help optimize stress transmission, whereas their biological inertness impairs osseointegration to a certain extent. This paper reviews the physical and mechanical properties, biological characteristics, and types of PEEK composites, as well as their applications in implants and abutments. In addition, it systematically summarizes the research progress of surface modification strategies for PEEK and the key challenges in clinical transformation, aiming to provide references for subsequent material optimization and clinical application.

Keywords: Oral implantation; Polyether ether ketone; Composite materials

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1. Introduction

Tooth loss or damage is mostly caused by trauma, dental caries, periodontal disease, and other factors, which may lead to tooth fracture or exfoliation, thereby impairing masticatory function, pronunciation, and facial aesthetics, and exerting adverse effects on patients' physical and mental health [1]. According to the Fourth National Oral Epidemiology Survey, the incidence of tooth loss is 32.3% among people aged 35–44 years old, and rises to 81.7% in those aged 65–74 years old [2]. At present, implant restoration serves as a vital treatment approach for dentition defects and edentulism, and its long-term efficacy largely depends on the mechanical properties, biocompatibility and osseointegration capacity of implant materials. Titanium and its alloys remain the predominant materials for current dental implants. However, their elastic modulus is much higher than that of alveolar bone, which easily causes stress shielding and induces peri-implant bone resorption. Meanwhile, wear and corrosion in the complex oral environment may trigger the release of titanium ions and particles, further inducing inflammatory responses and increasing the risk of peri-implantitis, thereby limiting its clinical application [3]. As a high-performance aromatic thermoplastic polymer, polyether ether ketone (PEEK) possesses favorable chemical stability, corrosion resistance and biocompatibility. Its elastic modulus is close to that of cortical bone, which can improve the stress transfer pattern to a certain extent and reduce the risks of stress concentration and bone resorption. Relevant studies have indicated that for periodontitis patients with missing incisors, PEEK adhesive bridge restoration can achieve satisfactory short-term therapeutic effects, effectively restoring the morphology and function of the anterior tooth region and improving aesthetic outcomes [4]. Therefore, combined with relevant literature, this paper summarizes the basic characteristics of PEEK and its composites as well as their applications in oral implantation. It is worth noting that although PEEK exhibits multiple theoretical advantages in the field of oral implantation, existing studies are mostly limited to in vitro experiments and finite element analysis, while long-term in vivo evaluations and clinical randomized controlled trials are still relatively scarce. The differences in actual restoration efficacy between PEEK and titanium implants remain to be further quantitatively compared.

2. Basic characteristics of polyether ether ketone and its composites

2.1. Physical and mechanical properties

Polyether ether ketone (PEEK) is a typical semi-crystalline aromatic polymer material. Its molecular main chain is composed of aromatic rings connected by ether bonds and ketone bonds, endowing the material with excellent structural stability and mechanical properties. In terms of physical properties, PEEK possesses high thermal stability and environmental resistance. It has a melting point of approximately 343 °C and can maintain favorable mechanical strength under high-temperature conditions. Meanwhile, it exhibits strong tolerance to acids, alkalis, and most organic solvents, and is not prone to degradation or corrosion [5]. From the perspective of molecular structure, the crystallinity of PEEK is generally between 30% and 40%. The synergistic effect of crystalline and amorphous regions enables it to combine rigidity and toughness. Compared with titanium alloy, the flexural strength of PEEK is about 140–170 MPa, which is lower than that of titanium alloy (approximately 900 MPa) but higher than that of human cortical bone (about 100–150 MPa), being sufficient to meet the requirements of oral implantation in non-weight-bearing or moderate-load areas. In addition, PEEK presents a relatively high level of wear resistance among polymer materials, with a friction coefficient of approximately 0.3–0.4, close to that of natural enamel, which provides favorable conditions for its application at implant-abutment junctions and prosthetic occlusal contact surfaces.

2.2. Biological characteristics

The application foundation of polyether ether ketone (PEEK) in the field of oral implantation mainly stems from its stable biocompatibility. Previous studies have shown that PEEK implants exhibit low immunogenicity in the in vivo microenvironment, hardly induce obvious inflammatory or toxic reactions, cause minimal irritation to surrounding soft and hard tissues, and can maintain a stable tissue interface. Meanwhile, it possesses a stable chemical structure, is resistant to degradation and the release of harmful products in body fluid environments, and thus maintains favorable biosafety under long-term implantation [6]. Nevertheless, PEEK itself exhibits a certain degree of bioinertness. It has low surface energy and lacks active functional groups, resulting in limited protein adsorption capacity. It cannot effectively mediate cell adhesion, as well as subsequent proliferation and differentiation, thereby hindering direct bonding between implants and bone tissue and limiting its osseointegration potential [7]. For instance, Han Hang et al. investigated surface microgroove fabrication on PEEK/mesoporous calcium magnesium silicate composites and found that materials without effective structural regulation showed relatively poor protein adsorption and low cellular response [8]. After optimization of the micro-nano surface structure, the material displayed markedly enhanced protein adsorption, promoted the adhesion, spreading, proliferation and osteogenic differentiation of rat bone marrow mesenchymal stem cells, and induced ordered cell growth along a specific direction. To further clarify the intrinsic mechanism underlying the bioinertness of PEEK, relevant studies have indicated [9,10] that the lack of polar functional groups on its surface leads to a water contact angle generally above 80°, presenting obvious hydrophobicity. Hydrophobic surfaces reduce the adsorption of extracellular matrix proteins such as fibronectin and osteopontin, thereby inhibiting integrin-mediated cellular signal transduction pathways. In recent years, research addressing this issue has evolved from simple surface hydrophilization to multi-strategy regulation of biological functions, including topological simulation of the extracellular matrix, loading of growth factors, and incorporation of anti-inflammatory drugs.

2.3. Types of polyether ether ketone composites

Existing studies have demonstrated that incorporating different types of reinforcing or functional components into the polyether ether ketone (PEEK) matrix can specifically regulate the overall performance of the material while retaining its characteristic low elastic modulus. According to the properties and action modes of the reinforcing phases, PEEK composites can be roughly divided into three categories [10]. The first category is fiber-reinforced composites, including carbon fiber, glass fiber, aramid fiber and others, which are mainly designed to improve the flexural strength and fatigue resistance of materials. Among them, short carbon fiber-reinforced PEEK (CFR-PEEK) has been clinically applied in orthopedic trauma fixation and spinal fusion devices. Its elastic modulus can be controlled within the range of 18–26 GPa by adjusting the fiber volume fraction, which is highly matched with human cortical bone (approximately 14–20 GPa). The second category is inorganic particle-filled composites, such as hydroxyapatite, tricalcium phosphate, bioactive glass and titanium dioxide, which are primarily used to enhance the bioactivity and osteoconductivity of the matrix. Compared with pure PEEK, the addition of hydroxyapatite at a mass fraction of 20%–30% can significantly increase surface roughness and protein adsorption capacity, and upregulation of alkaline phosphatase activity has been observed in in vitro experiments [11]. The third category is hybrid structural composites, in which two or more reinforcing phases are incorporated simultaneously, or a multi-layer structural design is adopted to achieve the collaborative optimization of mechanical and biological properties. For example, a double-layer structured implant with a core layer of PEEK/carbon fiber and a surface layer of PEEK/hydroxyapatite can provide favorable load transmission and osteoinductive interface simultaneously in a simulated body fluid environment. The main preparation technologies for the above composites include melt blending, solution casting and three-dimensional printing. Among them, three-dimensional printing technology has attracted widespread attention due to its capability to control the distribution gradient of reinforcing phases precisely.

3. Specific application of polyether ether ketone in the field of oral implantation

3.1. Dental implants

Yu Wanqi et al. also confirmed that the incorporation of carbon fiber enhances the mechanical properties of polyether ether ketone (PEEK) [12]. Notably, PEEK reinforced with 30% carbon fiber presents the optimal mechanical performance. Amino groups were successfully introduced onto its surface, which significantly improved the hydrophilicity and osteogenic properties of the material. Finite element analysis and in vitro studies have shown that under simulated masticatory loading conditions, PEEK implants and titanium implants share similarities in the overall stress transfer pathway and distribution range. Stress is mainly concentrated at the implant neck and the surrounding cortical bone area, without abnormal stress concentration or obvious deviation. Meanwhile, due to the low elastic modulus of PEEK, its stress transmission in bone tissue tends to be more uniform, which can alleviate local stress concentration to a certain extent [13]. In terms of biological performance, pristine PEEK is bioinert with a hydrophobic surface and limited protein adsorption capacity. It is difficult to directly induce cell adhesion and osteogenic differentiation, thereby restricting its osseointegration efficiency. Existing studies have demonstrated that constructing micro-nano structures or introducing bioactive components on the surface can enhance cell adhesion and proliferation on the material surface, upregulate the expression of osteogenesis-related genes, and accordingly improve the interfacial bonding between implants and bone tissue [14,15]. At present, various strategies have been developed for the surface modification of PEEK implants. Physical modification methods include plasma spraying, laser etching, sandblasting and acid etching, as well as ultraviolet grafting. For instance, oxygen plasma treatment can introduce oxygen-containing active groups (such as hydroxyl, carbonyl and carboxyl groups) on the PEEK surface, reducing the water contact angle from approximately 85° to below 40° and simultaneously increasing the surface free energy. Chemical modification methods include sulfonation treatment, dopamine self-assembly polymerization, and layer-by-layer self-assembly technology. Sulfonation treatment can form a porous three-dimensional network structure with adjustable pore sizes ranging from several micrometers to hundreds of micrometers, which not only facilitates cell contact and guidance but also provides space for loading bioactive molecules. In addition, biomolecule immobilization strategies, such as covalently grafting recombinant human bone morphogenetic protein-2 or arginine-glycine-aspartic acid peptides onto the PEEK surface, have been verified to promote osseointegration in animal models. It is worth noting that the combined application of different modification methods is usually more effective than a single approach, whereas the process complexity and repeatability still require further optimization.

3.2. Implant abutments

As a crucial intermediate component connecting dental implants and superstructure restorations, implant abutments are required to simultaneously meet multiple performance requirements, including mechanical stability, marginal adaptation, and soft-tissue compatibility under long-term functional loading and complex oral environments. In terms of biological adaptability, PEEK abutments can form a relatively stable interface with surrounding soft tissues. Their surface characteristics are conducive to epithelial attachment and connective tissue integration, which, to a certain extent, improves the sealing of peri-implant soft tissues and reduces plaque retention on the material surface. Meanwhile, compared with metal abutments, PEEK possesses a color similar to natural tooth tissues, hardly causing gray shadows in the gingival margin area, and presents greater advantages for the aesthetic restoration of anterior teeth. From the perspective of clinical operation, PEEK abutments exhibit excellent machinability and can be individually customized via computer-aided design and computer-aided manufacturing (CAD/CAM) technology, making them suitable for patients with thin gingiva or metal sensitivity. Nevertheless, PEEK abutments may face problems of creep and fretting wear during long-term service. A 5-year randomized clinical trial compared the single-crown restoration outcomes of zirconia abutments and PEEK abutments. The results showed no significant difference in implant survival rate between the two groups; however, the incidence of abutment screw loosening was slightly higher in the PEEK group. Therefore, some researchers have proposed improving the torque retention capacity of abutments by adding metal liners (such as titanium bases) or adopting composite reinforcing layers. In addition, the sealing performance at the connection interface between PEEK abutments and implants deserves close attention. Current in vitro studies suggest that its microleakage is equivalent to that of titanium abutments, while further in vivo data are still needed for verification.

4. Conclusion

Polyether ether ketone (PEEK) and its composites possess favorable fundamental advantages in mechanical properties, biological characteristics and structural design. With an elastic modulus close to that of bone tissue, they can optimize stress transmission and exhibit excellent chemical stability and biosafety. Aiming to address the limitations of PEEK, such as inherent bioinertness and insufficient mechanical performance, existing studies have mainly adopted improvement strategies, including fiber reinforcement, incorporation of inorganic components, and surface structure regulation, which effectively enhance the load-bearing capacity and interfacial bonding performance of the material. In clinical practice, PEEK has been applied to fabricate dental implants and implant abutments, showing satisfactory performance in mechanical adaptation and soft tissue response. Nevertheless, its osseointegration effect still needs to be further improved via targeted modification treatments. In the future, further in-depth application of PEEK in the field of oral implantation requires breakthroughs in the following aspects: First, to establish a standardized evaluation system for surface modification, so as to ensure the comparability of results from different studies and screen out the optimal modification protocols. Second, to conduct large-sample, long-term prospective clinical trials, so as to clarify the indication scope of PEEK implants in populations with different periodontal health status. Third, to develop functionally graded implants by adopting multi-material three-dimensional printing technology, which can meet multiple functional requirements, including soft tissue sealing, osseointegration, and stress buffering from the implant neck to the apical region. Fourth, to explore PEEK-based intelligent responsive materials, such as coatings loaded with antimicrobial peptides or pH-sensitive drugs, so as to actively regulate the peri-implant microenvironment and reduce the risk of peri-implantitis. It is anticipated that with the interdisciplinary integration of polymer materials science and oral regenerative medicine, PEEK is expected to become one of the important alternative materials in oral implantation following titanium and zirconia.

Disclosure statement

The authors declare no conflict of interest.

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