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Research progress on the application of polyetheretherketone in restorative dentistry

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Abstract: *Poly-ether-ether-ketone (PEEK) is an emerging organic polymer that is widely used in various fields of medicine because of its good biocompatibility, stable chemical properties, non-cytotoxicity, high temperature and friction resistance, and excellent mechanical properties. With its excellent overall performance, PEEK has shown strong momentum in the field of dentistry and is considered to be a promising restorative material that is expected to replace many existing materials, but its own shortcomings limit its clinical application and still needs to be improved by modification. This article reviews the application of PEEK materials in the field of restorative dentistry (including fixed, removable and implant restorations) and the latest research progress.*

Keywords: *polyetheretherketone; fixed restorations; denture materials; removable restorations; implant restorations*

1. Introduction

Poly-ether-ether-ketone (PEEK) belongs to the cyclic aromatic class of semi-crystalline thermoplastic polymers, formed by the polymerization of two ether bonds, a carbonyl and three benzene ring structure of the monomer[1], is a special engineering plastics with excellent mechanical properties and stable chemical properties. Polyetheretherketone has been introduced into the medical field by virtue of its good biosafety, ideal elastic modulus, high temperature sterilization resistance, corrosion resistance and radiation permeability, and has achieved recognized clinical results in intervertebral fusion, joint replacement, bone defect repair and plastic surgery[2、3]. As research into this material continues, PEEK and its composites are also making their mark in the field of dentistry, with applications in oral implants, prosthetics, maxillofacial surgery, and orthodontics[4]. Many researchers regard it as a promising new restorative material.

2. Application of Polyetheretherketone in the Field of Fixed Denture Restoration

2.1. Post-and-Core

Residual roots and crowns after root canal treatment usually require a pile core restoration first to provide retention and support for subsequent crown restorations and to enhance tooth resistance in the presence of insufficient remaining tooth tissue structure. The ideal root canal pile material should have high mechanical properties and, more critically, a suitable elastic modulus similar to the dentin elastic modulus (18.6 GPa) to match the physiological mobility of the tooth[5], reduce the stress concentration at the tooth-prosthetic interface during stressing, and protect the remaining tooth tissue[6]. The modulus of elasticity of polyetheretherketone is 3-4 GPa, which is closer to the dentin than the glass fiber piles (45.7-53.8 GPa) and metal alloy cast piles commonly used in current clinical practice.

Ibrahim et al. [7]compared the biomechanical behavior of PEEK piles, titanium metal prefabricated piles, and fiberglass piles by three-dimensional finite element analysis and found that PEEK piles exhibited a more favorable stress distribution pattern and higher fracture resistance at the intra-root dentin compared to titanium and fiberglass piles. The maximum stress of PEEK piles was located above the bone level and was more restorable even if root fracture occurred. YU et al.[8] came to a similar conclusion that PEEK reduces stresses at the bond interface between the pile itself and the binder compared to conventional materials, reducing the risk of debonding and vertical root fracture.

In an in vitro experiment, Attia et al. [9]reported that PEEK piles treated with 98% concentrated sulfuric acid showed significantly higher bond strength to the binder, and Benli et al. [10]also found that PEEK piles had higher tensile bond strength than metal and fiberglass piles when appropriate surface treatments and binder systems were used. Kasem et al. [11]demonstrated a clinical report of the use of PEEK pile cores cut by computer-aided design and computer-aided manufacturing (CAD/CAM) techniques for restoration of weak root canal incisors, and at 5-year follow-up, the patient had a good prognosis and was satisfied with the treatment outcome

Although a growing number of studies have reported excellent results with PEEK as a pile core material, more clinical cases and follow-up observations are needed to test its long-term restorative effectiveness.

2.2. Crown Restoration

The success of crown restorations depends on three key factors: biomechanical properties (wear resistance and fracture resistance), marginal fit, and aesthetics. Zirconia is currently the most commonly used material for full crown restorations due to its aesthetic, biocompatible, and superior mechanical properties to metals. PEEK, on the other hand, is considered a promising alternative material to zirconia.

The wear resistance and fracture resistance of PEEK have been studied by many authors, and Abhay et al. [12]reported less wear on the surface of PEEK crowns compared to zirconia crowns. Although PEEK crowns are more susceptible to displacement compared to zirconia crowns, they can exhibit more suitable stress regulation through deformation due to their much lower modulus of elasticity (3-4 GPa vs. 210 GPa). In terms of fracture resistance, Shetty et al. [13]found that the average fracture strength of PEEK crowns (2134.64 MPa) was significantly higher than that of zirconia composite crowns (1142.3 MPa) compared to zirconia.

Precise crown margins are the key to single-crown restorations, and failure can lead to dentin hypersensitivity, secondary caries, and many other complications. It has been found[14] that PEEK crowns have better marginal fit and internal crown adaptation compared to zirconia crowns.

Kavishma et al. [15]demonstrated the restorative effectiveness of PEEK crowns in a clinical setting. By applying PEEK crowns to the intraoral restorations of 20 patients, there was no significant marginal discoloration or occurrence of secondary caries at the 1-year interval follow-up, and the high-precision margins and excellent aesthetic results were recognized by the clinicians, while patients also expressed satisfaction with the comfort and aesthetics of the crowns.wns have better marginal fit and internal crown adaptation compared to zirconia crowns..Kimura et al. [16]also found no adverse effects of PEEK crowns on the marginal gingiva of the subjects through a 6-month clinical follow-up, and no decrease in chewing power.

2.3. Fixed Partial Dentures

The excellent properties of PEEK allow it to be used not only for single-crown fixed restorations, but also to meet the requirements for stress distribution and fracture resistance in fixed partial dentures (FDPs).PEEK has a much lower modulus of elasticity than cobalt-chromium alloy and zirconia, so when pressure is applied to the denture, PEEK regulates the stress and prevents fracture of the abutment[17].In a finite element analysis[18] comparing the mechanical properties of acrylic, resin composite, and PEEK three-unit FDPs, it was found that in a PEEK denture, the joint provided greater stress distribution at the connector than the rest of the denture, and that PEEK relieved the stress concentration in the FDPs. In an in vitro study, Stawarczyk et al.[19] found that PEEKFDPs digitally cut using CAD/CAM had lower deformation and higher fracture resistance than FDPs made from PEEK particles by vacuum pressurized injection molding. Rodríguez et al. [20]compared the fracture loads of metal, PEEK and zirconia in an in vitro simulation experiment, PEEK was second only to metal and higher than zirconia, and all three had fracture load values higher than 1000 N. Maximum occlusal forces of 150 to 300 N have been reported for anterior teeth, 200-445 N for premolars, and 900 N for molars, thus demonstrating that PEEK restorations are adequate for everyday chewing applications. For clinical applications, Rauch et al.[21] compared different tooth-colored CAD/CAM restorative materials and found that PEEKFDPs were lighter in mass and shorter in fabrication duration than zirconia FDPs, although the aesthetic results were slightly worse than those of zirconia, but within acceptable limits.

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3. Application of Polyetheretherketone in the Removable Partial Dentures Restoration

3.1. Denture Base

Due to their large size, removable partial dentures (RPDs) often produce a significant foreign body sensation when worn in the patient's mouth. Advances in digital technology have allowed PEEK to be cut by CAD/CAM into a denture base that better fits the patient's mouth[22]. It overcomes the defects of metal RPD framework with unattractive color, metallic smell and possible allergic reactions.

PEEK can be fully digitally processed. All denture components can be designed and digitally manufactured using intraoral scanning and assembled without physical casting, significantly reducing denture fabrication time. Arnold et al. [23]compared PEEK denture bases with cobalt-chromium denture bases that were fabricated using different methods, including lost wax techniques, cutting, and selective laser melting. The results showed that the PEEK substrates had the lowest distortion and the best fit.Chen [24]analyzed the mechanical properties of cobalt-chromium alloy, titanium alloy, and PEEK denture abutments by the three-dimensional finite element method. In the study, the PEEK abutment exerted less stress on the abutment periodontium and had a more uniform distribution of masticatory forces than the metal alloy framework abutment. The PEEK abutment had good protection for periodontal tissue and could be used in patients with poor periodontal condition. However, the maximum displacement of the free end under masticatory forces is not conducive to the stability of the denture, and the stress on the mucosa is higher, suggesting that PEEK is not suitable for patients with a large number of missing posterior teeth with a free end denture.A randomized controlled trial[25] has looked at oral health-related quality of life (OHRQoL) in patients with edentulism treated with cobalt-chromium and PEEK removable dentures. It was found that both materials significantly improved the OHRQoL of patients.A clinical study [26]showed no significant difference in vertical height and three-dimensional changes in the alveolar ridge between patients wearing a digitally fabricated PEEK removable denture and those without a removable denture during a short-term evaluation period of 1 year. Thus, a removable denture with a PEEK base may be ideal for preserving the remaining alveolar ridge.In a clinical report[27], Harb performed a metal-free framework denture for a female patient with a dissatisfied metal RPD. A PEEK metal-free framework was constructed using CAD/CAM and digital cutting techniques to obtain a maxillary removable denture that fit in the patient's mouth and was functionally and aesthetically satisfactory, although the patient reported reduced retention.

PEEK is stronger, color adjustable, and less dense, producing a lighter denture, but digitally cutting PEEK is more expensive than traditional dewaxing techniques and metal RPD frameworks, and remains a factor for patients to consider.

3.2. Retainer

Retainers are the main retainers for removable denture restorations, which are directly attached to the abutment teeth to provide retention, support and stability. Commonly used retainer materials are usually metal, such as titanium and cobalt-chromium. PEEK rings can be adjusted to match the color of the patient's natural teeth and can also simulate the color of the gums[28].Htun et al. [29]used the CAD/CAM technique to fabricate tooth-colored PEEK aesthetic retainers for a 25-year-old female patient with mandibular edentulism, who was very satisfied. No changes in the retainer were observed at 3 and 6 months of follow-up. However, unlike metallic materials, PEEK materials are rigid and the ability to meet the retention force requirements of a removable denture is an issue to be considered. Therefore, a number of researchers have validated the retention force of PEEK retaining rings. EL-BAZ et al.[30] evaluated the retention force, fatigue resistance, and deformation properties of both cobalt-chromium and PEEK rings through in vitro simulations, and concluded in their study that: a PEEK ring (1.0 mm cross-sectional diameter) joined with a concave edge of 0.50 mm can provide the same retention force as a cobalt-chromium ring. Peng et al. [31]used finite element analysis to compare the load values and deformation of PEEK and cobalt-chromium snap rings. The authors found that the specifications of cobalt-chromium alloy snap rings were not applicable to PEEK, and by optimizing the snap ring shape of PEEK: a width of 3 mm, a bottom thickness of 2.25 mm, and a taper ratio of 0.5, the PEEK snap ring was able to meet the requirements for retention force (5-10 N) in clinical use. The experiments simulated a 10-year clinical service life of the snap ring, and the two showed different deformation characteristics in the early cycles, but there was no significant difference in the long-term deformation of the two materials. Zheng et al. [32]studied the stress-fatigue behavior of cast and laser sintered cobalt-chromium and PEEK snap rings. The PEEK material has the highest fatigue resistance and lower flexural resistance to provide adequate retention.

Although CAD/CAM-made retainers and frames are currently used in clinical practice, there is a lack of long-term systematic evaluation and PEEK cannot yet replace metal retainers and brackets in removable partial dentures.

3.3. Other Removable Partial Dentures Restoration

PEEK can also be fabricated into attachments, and Sadek et al.[33] found that when PEEK was used as a precision attachment, it showed good stress distribution and reduced strains around the abutment and alveolar ridge, especially in distal abutments. One study reported[34] that sleeve crowns made of PEEK maintained the highest retention force when both the inner and outer crowns were made of PEEK, and the frictional force between the inner and outer crowns remained constant in long-term experiments.

4. Application of Polyetheretherketone in Implant Restorations

4.1. Dental implants

Although titanium is the most common implant material used in clinical practice, it has some disadvantages, such as high modulus of elasticity, which may cause stress shielding and peri-implant bone resorption, allergic reactions to titanium implants in a few patients, and poor aesthetics due to its metallic color. Therefore, researchers are also looking for a better alternative material. Polyetheretherketone is non-toxic and non-allergenic to humans, and its radiolucent properties not only reduce the appearance of artifacts on magnetic resonance imaging (MRI), but also allow for clearer observation of bone regeneration and healing around the implant. It has a modulus of elasticity closer to that of human alveolar bone than titanium, and its mechanical properties can be adjusted after modification to improve its biological inertia and poor osseointegration. Therefore, many scholars consider it as a non-metallic implant material that can replace titanium.

PEEK implants were introduced by Invibio in the UK in 1998, and with the advent of commercial PEEK implants, there has been an increase in research to improve their various properties.In terms of improving mechanical properties, the addition of inorganic particles and fibers to PEEK through blending modification can improve the elastic modulus of PEEK, which is commonly found in carbon fiber reinforced PEEK (CFR-PEEK) composites and glass fiber reinforced PEEK (GFR-PEEK) composites, which can have elastic moduli as high as 18 GPa and 12 GPa[35].While the modulus of elasticity of human cortical bone is 18 GPa, according to Wolff's law [36], the closer the elastic modulus of the implant is to the surrounding bone, the better it is for bone healing.A finite element analysis [37]was performed to evaluate the bone stress and deformation of Ti and CFR-PEEK implants with a length of 11.5 mm and a diameter of 5 mm, and a load of 150 N was applied to the long axis of the implant, resulting in similar deformation and stresses in the bone, which led to the inference that CFR-PEEK could be an alternative material to titanium implants]. Haseeb et al. [38]compared GFR-PEEK with Ti in a similar way and concluded that GFR-PEEK could replace titanium as a new implant material as well as CFR-PEEK.

With the development of various modification methods, the mechanical properties and bioactivity of PEEK have been improved and optimized, but more in vivo experiments and clinical studies are needed to validate them if they are to be widely used in implant restorations.

4.2. Planting Abutments

The implant abutment is one of the essential accessories for dental implant restorations. It is the connecting part between the implant and the crown and provides retention, stability and support for the crown of the superstructure. The abutment affects the characteristics of the hard and soft tissues surrounding the implant, and the selection of a suitable restorative abutment plays an important role in improving the retention of the implant and in enhancing the aesthetic effect of the restoration. The most commonly used abutments are pure titanium abutments, but they are not aesthetically pleasing. When using pure titanium abutments, the gingival soft tissue needs to be more than 3 mm to ensure that the metal color is not exposed, so all-ceramic abutments and PEEK abutments are considered to be an alternative to titanium for the aesthetic area of anterior dental implants.

The average fracture toughness of Ti abutments was reported to be 468.5 N and that of PEEK abutments was 200.4 N[39]. Fatigue testing was performed at 140 N for 2 million cycles, equivalent to 5 years of service life, and no damage was observed in either case. Peng et al. [40]compared the cytotoxicity of PEEK with conventional implant abutment materials (i.e., titanium alloy and zirconia) to assess the cellular metabolic activity, cytotoxicity, and inflammatory potential of human oral fibroblasts (HOF) on these materials. PEEK showed comparable cytotoxic and pro-inflammatory effects to those of i.e., titanium alloy and zirconia, and is a suitable abutment from the perspective of biological behavior materials. The biocompatibility of three different abutment surfaces, titanium, zirconia and modified PEEK, was compared in in vitro experiments, and the modified PEEK abutment surface could enhance biocompatibility by positively influencing the viability, adhesion, migration and proliferation of human gingival epithelial keratin-forming cells compared to titanium and zirconia. This study suggests that PEEK may be an equivalent or even better alternative material in terms of soft tissue cell biocompatibility[41].In a controlled clinical trial[42], titanium and PEEK healing abutments were used in 16 patients who underwent implant restorations. The results showed that PEEK did not increase the risk of marginal bone loss and soft tissue regression and was not significantly different from titanium abutments at 2 weeks and 3 months postoperatively.AL-Rabab'ah et al. [43]used PEEK material as a permanent abutment in maxillary central incisor implant restorations, and after two years of follow-up, the peri-implant bone and soft tissues remained stable, but the long-term clinical outcome is still lacking evaluation.

5. Conclusions

As a promising biomaterial, although a number of studies have reported the application of PEEK in the field of dental prosthetics, there is still a lack of long-term clinical applications to verify its utility and stability. Moreover, PEEK still has some drawbacks in terms of aesthetics and biological inertness, which need to be optimized by various structural or functional modification methods. It is believed that with the continuous development and advancement of digital technology and material processing and modification methods, PEEK is expected to better meet the needs of individualized dental prosthetics.

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