PEEK High Performance Polymers: A Review of Properties and Clinical Applications in Prosthodontics and Restorative Dentistry

Keywords

Fixed Dental Prosthesis
PEEK
High Performance Polymers
Removable Dental Prosthesis
Resin Bonded Crown Restoration
Implant Abutment

Authors

Elli Alexakou *
(DDS)

Marianna Damanaki §
(DDS)

Prof. Panagiotis Zoidis ‡
(DDS, MS, PhD)

Eleonora Bakiri ^
(DDS)

Nikolaos Mouzis ‡
(CDT)

Greta Smidt †
(DDS, Dr. Odont)

Stefanos Kourtis Δ
(DDS, Dr. Odont)

Address for Correspondence

Prof. Panagiotis Zoidis ‡
Email: pzoidis@dental.ufl.edu

* Dentist in private practice, Athens, Greece

§ AEGD Resident, University of Connecticut Health Center, USA

‡ Clinical Associate Professor, Department of Restorative Dental Sciences, Division of Prosthodontics, University of Florida College of Dentistry, Gainesville, USA

^ Clinical Assistant Professor, Department of Restorative Dental Sciences, Division of Prosthodontics, University of Florida College of Dentistry, Gainesville, USA

† DMD Candidate, University of Florida College of Dentistry, Gainesville, USA

Δ Associate Professor, Department of Prosthodontics, National and Kapodistrian University of Athens, Greece

Received: 19.12.2018
Accepted: 10.07.2019
doi: 10.1922/EJPRD_01892Zoidis09

ABSTRACT

Various materials have been used over time in prosthetic dentistry. However, due to the evolution of science and knowledge, new materials are being brought to the forefront. Polyether ether ketone (PEEK) is a polymer with many potential applications in dentistry. The use of PEEK has become increasingly more common in dental practice; its favorable properties have made it a compelling alternative biomaterial in restorative dentistry. The current trend is moving towards the use of metal-free restorations and biomaterials which exhibit advanced properties in the complex oral environment. This review paper presents and summarizes clinical applications of PEEK in contemporary dentistry.

INTRODUCTION

Metal alloys, titanium and zirconia are currently the materials most commonly used for the fabrication of conventional prostheses and implant restorations. The forefront of dental research is geared towards high performance polymer materials in order to improve framework properties and potentially reduce the overall cost of prosthetic tooth rehabilitation. This review was conducted in PubMed using as keywords PEEK, and different dental disciplines such as implant dentistry, periodontics, prosthodontics, orthodontics and restorative dentistry.

PEEK is a high impact polymer material with mechanical and physical properties resembling those of bone. PEEK has also been found to have biocompatible properties; this combination of favorable *in vivo* and *in vitro* findings has made PEEK very popular for medical applications, such as spinal and orthopedic implants,[1-3] while its potential for dental applications have also been researched over the last decade. The use of PEEK has been advocated for many types of intra-oral fixed and removable prosthetic restorations.[4,5] PEEK has also been used for the fabrication of esthetic orthodontic wires, as it may exert more favorable orthodontic forces than conventional orthodontic wires.[6]

PHYSICAL AND MECHANICAL PROPERTIES

Polyetheretherketone is what is known as a high performance polymer. PEEK's polymer molecular chain configuration allows for enhanced physical and mechanical properties when compared to other polymers. The physical and mechanical properties of PEEK are summarized in Table 1.

Table 1. Physical and mechanical properties for PEEK.[7,8]

Mechanical properties	
E modulus	4,000 MPa
Flexural strength	> 150 MPa
Water absorption	6.5g/mm^3
Water solubility	< 0.3g/mm^3
Breaking load tests on three-unit FDPs	
Max stress without fracturing (no cycling)	> 1,200 N
Max stress without fracturing (mechanical & thermal cycling)	> 1,200 N
Other properties	
Melting range	Approx 340°C
Bond strength	> 25 MPa
Density	1.3-1.5cm^3
Hardness	110 HV

SOLUBILITY

PEEK has a water solubility of 0.5 w/w% and it cannot be chemically affected by long-term water exposure, even at temperatures of up to 260°C.[2] In a study of Liebermann *et al.*[9] of the physical and mechanical characteristics of PEEK and other modern esthetic CAD/CAM polymer materials, PEEK showed lower solubility and moisture absorption, while hardness values were comparable to those of PMMA materials.

ELASTIC MODULUS

PEEK presents a semi-crystalline structure, which makes it less brittle than zirconium dioxide (a crystalline structure). PEEK's modulus of elasticity is 3.1 GPa (similar to that of bone), which is also a great advantage for use in implant dentistry. Zirconium oxide and non-precious metals are more rigid materials, having a modulus of elasticity of 100 GPa.[10]

Moreover, PEEK can be easily modified by incorporating other materials like carbon fibers which may increase the elastic modulus up to 18GPa.[11] Since PEEK's modulus approximates that of dentine and cortical bone,[12-14] it could also result in the reduction of stresses transferred on the abutment teeth and also the cementation interface, when compared to titanium and other materials.[4,15] The tensile strength and Young's modulus are summarized in Table 2.

Table 2. Tensile strength and elastic moduli of PEEK, CFR-PEEK, PMMA and mineralized human tissues.[7,8]

Material	Tensile strength (MPa)	Young's modulus (GPa)
PEEK	80	3-4
CFR-PEEK	120	18
Cortical bone	104-121	14
PMMA	48-76	3-5
Dentin	104	15
Enamel	47.5	40-83
Titanium	954-976	102-110

WEAR RESISTANCE, FLEXURAL AND TENSILE STRENGTH

Despite its significantly low elastic modulus and low hardness, PEEK's wear resistance is comparable to that of metal alloys.[16] PEEK exhibits greater wear resistance during lateral force application and similar abrasion rate, compared to resin materials when opposing natural teeth.[17]

In a three-point bending test conducted by Schwitalla *et al.*,[18] PEEK, exhibited higher values than the prevailing minimum strength for plastic materials (65MPa). Concerning its use in orthodontics, PEEK exhibited the highest flexural strength and creep resistance among other plastic alternatives (PES and PVDF).[19] PEEK's tensile strength stands at 80 MPa.[20] The tensile properties of PEEK are similar to those of enamel and dentin,[21-23] which also makes it suitable for framework fabrication of prosthodontic restorations.

BIOLOGICAL PROPERTIES

There is sufficient scientific evidence which suggest that PEEK and PEEK composites are biocompatible materials.[24] Sensitivity tests displayed negative results and tests for gene toxicity showed no chromosomal abnormality due to PEEK.[25-31]

There is currently no evidence to suggest any potential cytotoxic, mutagenic, carcinogenic, or immunogenic activity.[32] Its extensive use in orthopedics also advocates for the biocompatibility of the material.

PEEK acts as a relatively bio-inactive material with limited fixation to bone, a property which has been a subject of investigation in numerous studies.[33,34] There is a relation between the implant stiffness and bone resorption around the implant fixture nicely explained by Wolff's law and stress shielding effect. Wolff's Law dictates that the density of bone is dependent on its stress condition. If the applied stress environment of a load-bearing bone region is decreased below its normal physiological levels, the bone density of that region can decrease leading to a reduction in strength, the degree of which is directly related to the stiffness of the implant material.[35]

Stiff implants fabricated from Ti or ZrO^2 do not adequately strain the bone, which can result in disuse atrophy and bone resorption.[36] This phenomenon is known as stress shielding and leads to bone resorption and eventually loss of osseointegration.[37-38] PEEK implants are less stifer than Ti or Zr and are known to reduce this stress shielding effect.[39]

In order to improve the bone-to-PEEK implant interface, various composition modifications have been proposed, such as the creation of hydroxyapatite composites, coating PEEK with titanium and Hydroxyapatite, network creation for bone ingrowth, as well as combination with phosphate-calcium biomaterials and other modifications.[40-47]

PEEK is strongly indicated for patients with allergies as an alternative material to metal alloys, due to its low solubility and its low reactivity, intraorally.[7] A single report to a chronic allergic reaction has been recorded to PEEK with regards to a patient who underwent an implantation of intervertebral PEEK cage. The patient developed angioedema-like symptoms with intense redness, itching, tongue swelling and skin thickening. The skin patch test showed a positive result for PEEK and symptoms were resolved with implant removal.[48]

PEEK FORMS FOR DENTAL USE

Mainly two commercial brand types of PEEK are used in the dental and medical fields. PEEK-OPTIMA, is used primarily in the United States of America, whereas BioHPP is used in Europe. Both products represent modified PEEK material with enhanced properties.

PEEK-OPTIMA™

PEEK-OPTIMA™ is the first thermoplastic implantable material, developed in 1999 by Invibio Biomaterial Solutions Co. It is a poly-aromatic semi-crystalline thermoplastic material with a melting temperature of ~343°C, a crystallization peak of ~160°C and a glass transition temperature of ~145°C. Three natural (unfilled) grades are available as high, medium and low viscosity variants and are generally known as poly-aryl-ether-ketones. The addition of carbon fibers improved properties such as hardness and creep resistance. PEEK-OPTIMA™ is currently used in dentistry for temporary prosthetic abutments, healing screws, precision attachments and implant-supported restoration frameworks. Conventional laboratory fabrication includes melting and injection molding. Using CAD-CAM technology, PEEK "blanks" (Juvora) can be used to mill frameworks for dentures or FDPs within minutes.[49]

BIOHPP™

BioHPP™ (Bio High Performance Polymer) was developed by Bredent GmbH specifically for dental applications. This PEEK material modification includes the addition of ceramic fillers with grain size between 0.3-0.5mm. According to the manufacturer, the small grain size is responsible for homogeneity and improved polishing properties. Injection molding as well as CAD-CAM options are also available for this material. BioHPP is approved by the manufacturer for three to four-unit FDPs, telescopic restorations, implant abutments, and secondary structures associated with bar-supported prostheses.[8]

CLINICAL USE OF PEEK IN DENTISTRY AND PROSTHODONTICS

IMPLANT ABUTMENTS - HEALING SCREWS-FRAMEWORKS

PEEK has been used for the manufacturing of implant prosthetic abutments by various implant companies. A randomized controlled clinical trial (RCT) by Koutouzis *et al*.[50] suggests that there is no significant difference in bone resorption and soft tissue inflammation around PEEK when compared to titanium abutments. Additionally, the microbial oral flora was similar to titanium, zirconia or PMMA abutments.[51]

Rea *et al*,[52] evaluated soft and hard tissue healing using different forms of PEEK healing screws. The authors concluded that PEEK may be used as a healing screw material, since no statistical difference was observed between PEEK forms and titanium.

Moreover, Maté Sánchez de Val *et al*.,[53] studied the behavior of PEEK as a material for implant prosthetic abutments and concluded that the biocompatibility of the material, in combination with its excellent tissue response, made it a suitable alternative to conventional titanium abutments. The material has also been used for framework fabrication on short *(Figures 1a-b)* or long span all-on 4 implant restorations *(Figures 2a-b)*, providing a cushioning effect as a distinct advantage over harder materials, resulting in less screw loosening or even veneer chipping and repairs.

Figure 1a-b: PEEK three unit implant prosthesis. a) FDP framework. b) Definitive FDP.

Figure 2a-b: PEEK all-on-4 implant prosthesis. a) FPD framework. b) Definitive FPD.

REMOVABLE DENTAL PROSTHESES (RDPS)

Removable Dental Prostheses (RDPs) frameworks can be fabricated from PEEK, using either injection molding or CAD/CAM systems. Tanous *et al.*[54] suggested that PEEK clasps have less retaining capability as when compared to chromium-cobalt clasps. Despite this, PEEK clasp retentive features remained stable over time. However, since the study was conducted *in vitro*, the authors determined that it would be necessary to evaluate the clinical behavior of the material in order to support clear conclusions. Similarly, more studies are needed to evaluate the efficacy of PEEK obturators as compared to conventional acrylic prostheses.

Zoidis *et al.*[55] have presented the use of PEEK as the framework material for distal extension RDPs *(Figures 3a-b)*. It is indicated in patients allergic to metals or disturbed by the metallic taste, the weight and the unpleasant appearance of metal in their mouth. Also, overdenture frameworks are fabricated from PEEK to promote proprioception as well as cushioning effect to underlined teeth and supporting structures.[56]

FIXED DENTAL PROSTHESES (FDPS)

The use of modified PEEK for single crown frameworks veneered with light polymerized composite resin has been suggested in case of patient metal allergies and weak abutments for patients with strong masseters or parafunctional habits.[57,58] The same light-polymerized composite material has been used to veneer PEEK endo-crown frameworks with predictable results.[59] Wagner *et al.*[60] studied the retention between PEEK telescopic crowns and cobalt chrome copings of different taper and manufacturing methods *(Figures 4a-b)*. Milled crowns with 0° taper showed the lowest retention. Manufacturing process did not significantly affect the retention of 1° and 2° taper crowns, while tapers did not significantly affect the retention of PEEK crowns manufactured by injection molding.

CAD-CAM systems are also used for the fabrication of longer span FDPs *(Figures 5a-b)*.[61] CAD-CAM FDPs frameworks fabricated from composite or PMMAs, present better mechanical properties compared to conventionally fabricated prostheses from the same materials.[62,63]

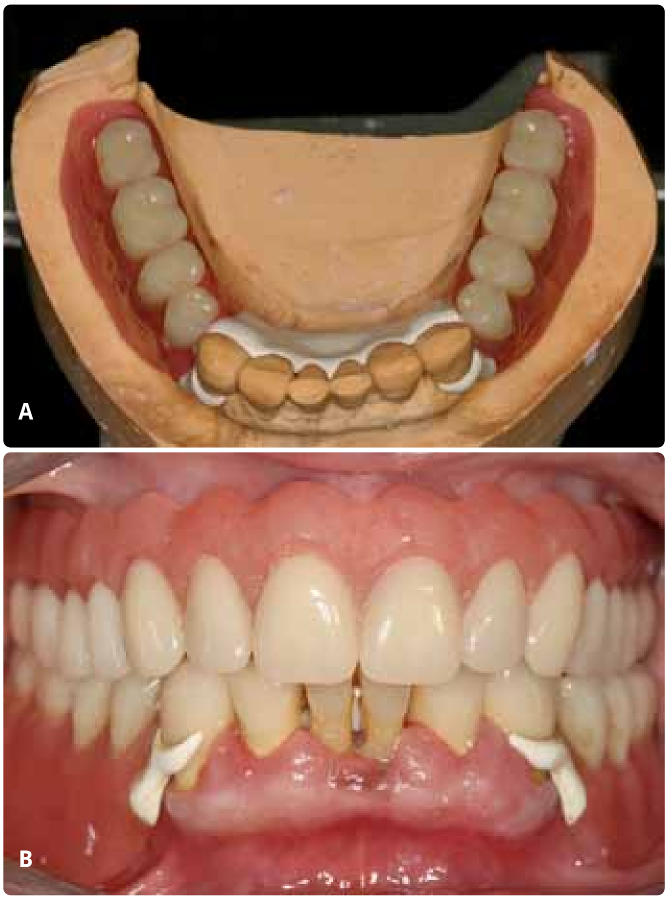

Figure 3a-b: PEEK RDP. a) In the master cast. b) Intraoral view

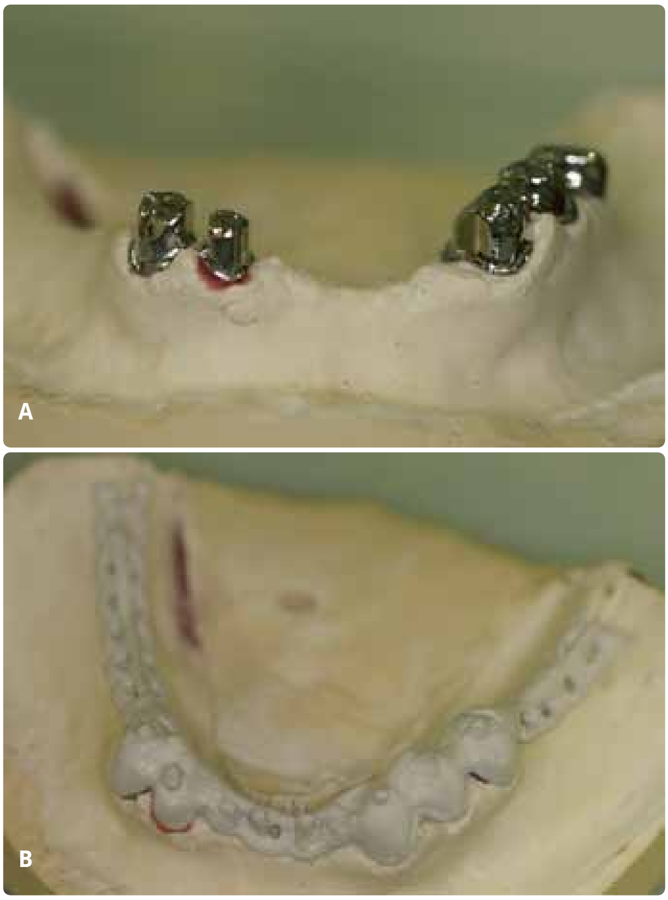

Figure 4a-b: Telescopic RDP. a) Primary telescopic crowns. b) Secondary PEEK framework

PEEK can be used as an alternative to PMMA for such restorations. It has been suggested that a CAD-CAM three-piece PEEK FDP has a higher tensile strength compared to a compacted granular- or pellet- shaped PEEK denture.[64] The breaking strength of PEEK FDPs frameworks is much higher (1200N) than that of lithium disilicate (950N), alumina (851N) or zirconia (981-1331N).[65]

RESIN BONDED RETAINED (RBR) FDPS / SPLINTS

PEEK has been used for conservative RBR (resin bonded retained) single tooth restorations *(Figures 6a-b)*. In a clinical case presented by Andrikopoulou *et al.*,[15] restoring the anterior maxillary area in a patient with lip-cleft palate, a PEEK framework coated with resin has been fabricated to restore a missing lateral and to splint the remaining anterior teeth. The authors suggest that the low modulus of PEEK, in combination with the use of indirect composite resin as a coating material, provide a distinct advantage over ceramic and metal-ceramic restorations because, as a result of these properties, the occlusal forces are significantly dampened, reducing the risk of debonding.

The use of modified PEEK has also been proposed for fabricating Maryland bridges for in cases of abutment teeth with different mobility patterns. The dampening of occlusal forces by the PEEK framework may contribute to decreased debonding rates and increased survival rates.[66]

CLINICAL CONSIDERATIONS

BONDING WITH VENEERING MATERIALS

A lot of research has been conducted on PEEK surface modification in order to explore the bond between PEEK and veneering materials such as composite resins. Although air-abrasion with or without silicon dioxide coating leaves the surface of PEEK more prone to moisture,[67] etching with phosphoric acid creates a rough and chemically modified surface that allows a stronger bond of the material with the hydrophobic composites (shear bond strength: 19.0±3.4 MPa).[4]

Etching with phosphoric acid for 60 to 90 secs may result to shear bond strength with composite resin cements up to 15.3±7.2MPa after storage in water 37°C for 27 days.[68] A bond of 23.4±9.9MPa with the composites has been achieved in aged PEEK samples by combining etching with piranha acid (a mixture of sulfuric acid H_2SO4 and hydrogen peroxide H_2O_2) and the use of adhesive agent.[69]

ejprd.org - Published by Dennis Barber Journals.

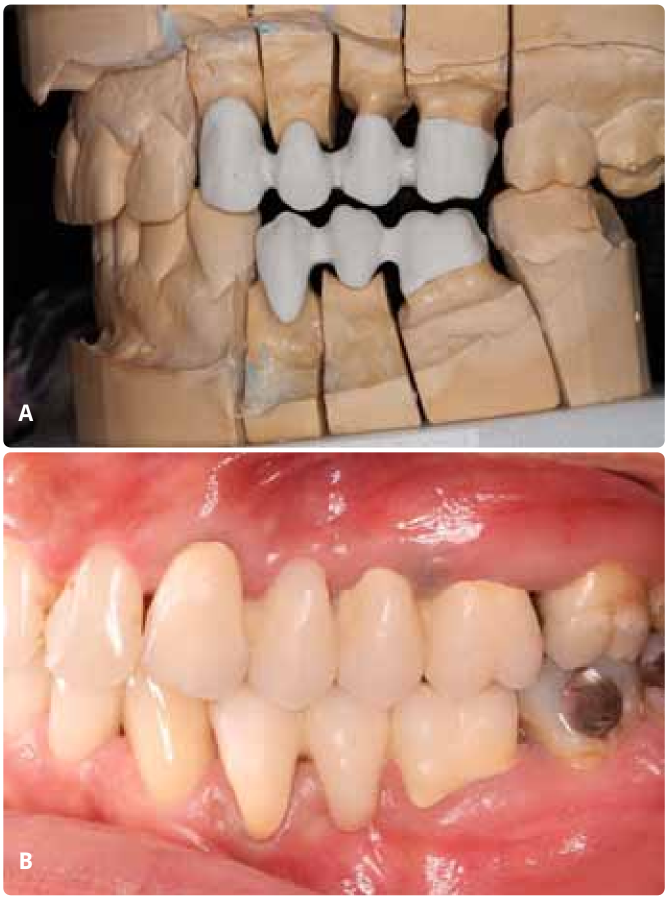

Figure 5a-b: Four unit FDP. a) Peek frameworks. b) Hi-impact composite veneer.

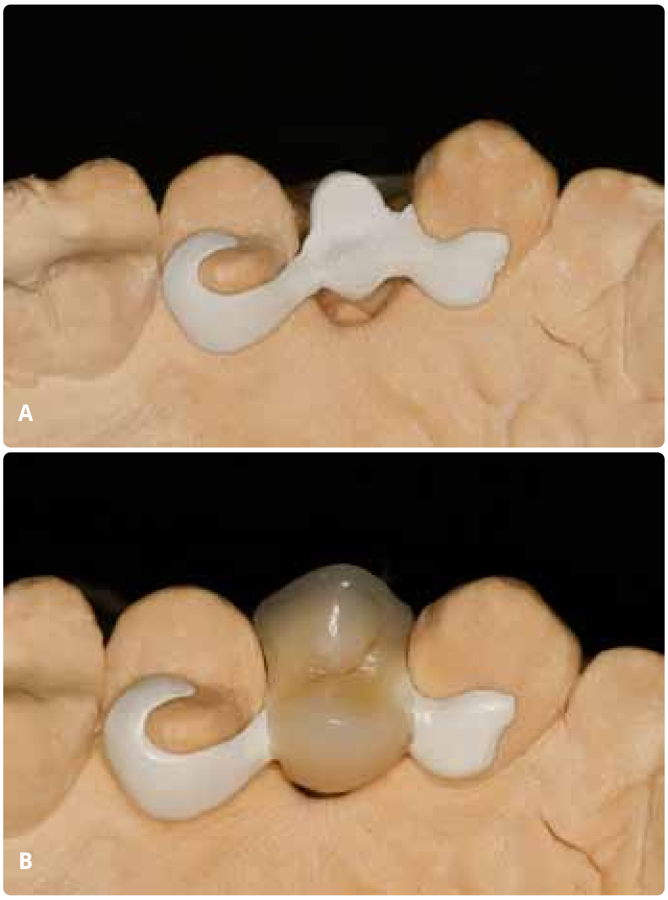

Figure 6a-b: RBR restoration. a) Peek framework. b) Hi-impact composite veneer pontic.

Keul *et al.*[68] proposed etching the surface with phosphoric acid or argon plasma, as it resulted in statistically significant difference in bond strength compared to preparing surfaces with hydrofluoric acid and air-polishing with 50μm grained Al_2O_3. The use of resin cement SE Bond/Clearfil AP-X™ also showed statistically greater bond strength compared to RelyX™ Unicem.

Kern *et al.*[70] proposed surface air-abrasion and use of primer Luxatemp Glaze & Bond with methyl methacrylate, while Uhrenbacher *et al.*[71] support that the adhesion after surface preparation with air-polishing or etching with phosphoric acid and/or use of an adhesive system, such as visio.link or Signum PEEK Bond, is satisfactory.

Stawarzyk *et al.* studied the effect of different preparation and bonding methods in load-bearing of veneered three-piece PEEK FPDs.[72] They concluded that there were no statistically significant differences between the various methods of etching and bonding. However, it is important to note that findings implied that coating with Signum Composite seemed to exhibit higher overall resistance to load-bearing when compared to coating with Singnum Ceramis. No PEEK framework fractures occurred after loading, however cases of chipping of the veneering material were observed. In another study of Stawarzyk *et al.*,[73] etching with acid is proposed as the most appropriate method of bonding PEEK with coating resins. Although the above studies do not agree on a common preparation protocol of PEEK surface for bonding with resins, the overall conclusion is that PEEK can be safely used as a coping material veneered with composite resins.

DISCOLORATION OVER TIME

In a study on the discoloring agents for polymeric materials, Heimer *et al.*[74] stated that the least discoloration was observed in samples stored in distilled water and chlorhexidine, followed by those in red wine. Carry solution caused the greatest discoloration. Notably, PEEK showed the smaller color change compared to resins and PMMA materials. The most effective method for pigment removal was the ultrasound bath and the Air Flow Plus. The least effective methods were the preventive brushing with soft or medium-hard toothbrush and the SunSparkle professional cleaning system. The authors suggested informing patients about the possibility of discoloration from various foods, and advised personal cleaning with toothbrush, professional cleaning by air-polishing with mild powder and laboratory cleaning with mild methods, such as ultrasonic bath.

CLEANING METHODS

Heimer *et al.*[75] also studied various cleaning methods for PEEK and suggested brushing with a soft, medium-hard and sonic toothbrush, laboratory cleaning with Sympro, SunSparkle system and ultrasonic bath, professional preventive cleaning with Perio Soft-Scaler, Sonicsys, Air Flow Comfort and Air Flow Plus. Professional air-polishing with Al_2O_3 grains is not considered safe.

According to another study, the air-polishing treatment and the polishing procedures with Zirpolish paste lead to a surface with greater roughness, facilitating the retention of dental plaque. According to Sturz *et al.*,[76] the increased contact angle values after polishing can be decreased, by coating PEEK with DMA-nano components. In conclusion, the use of such polishing appliances for PEEK restorations is better to be avoided.

COMPARISON OF PEEK WITH OTHER MATERIALS

PEEK is a biologic, high impact polymer material used for the fabrication of metal-free restorations, reducing the possibility of allergic reaction or any corrosion phenomena.

Its low specific weight results in lighter restorations when compared to metal alloys. Compared to ceramic framework fabrication materials, PEEK is the only material to exhibit a stress absorbing effect and less brittle behavior. The similarity to the modulus of elasticity of bone, may also indicate its use in implant restorations where the periodontal ligament is missing.

PEEK has improved biocompatibility and is extensively used in orthopedics. For intra-oral use, the low plaque accumulation and the low moisture absorption may advocate its use. It is questionable, however, if the material's surface polish can be compared to glazed ceramic or industrially fabricated titanium parts.

PEEK frameworks can be fabricated either conventionally or by the use of CAD/CAM technology at a lower cost when compared to ceramic materials. The use of light-polymerizing polymer veneering materials also simplifies the fabrication procedure, reducing time and cost.

Another major clinical advantage of PEEK restorations is the possibility of intra-oral repair of the veneering material in cases of chipping without restoration removal.

A clinical issue that has not been investigated is the fatigue strength of PEEK frameworks due to lack of *in-vitro* studies. The long-term bond strength of polymer veneering materials on PEEK frameworks needs to be confirmed by both *in-vitro* and *in-vivo* studies. Lastly, the overall clinical performance of PEEK has to be investigated in long term clinical trials before extensive clinical use of this new material can be recommended.

CONCLUSION

PEEK is a biocompatible material with favorable properties that allow for its use in restorative dentistry for various treatment options and applications. Research and clinical data shows promising results in regards to the use of PEEK intraorally, however, the current data needs to be further analyzed and knowledge gaps should be identified and explored in order to establish PEEK as a viable alternative biomaterial for successful restorative treatments in dentistry.

REFERENCES

1. Toth J, Wang M, Estes B, Scifert J, Seim H, Turner A**:** Polyetheretherketone as a biomaterial for spinal applications. *Biomaterials* 2006;**27**:324–34.
2. Kurtz S, Devine J. PEEK biomaterials in trauma, orthopedic, and spinal implants. *Biomaterials* 2007;**28**:4845–69.
3. Pokorny D, Fulin P, Slouf M, Jahoda D, Landor I, Sosna A. Polyetheretherketone (PEEK). Part II: Application in clinical practice. *Acta Chir Orthop Traumatol Cech* 2010;**77**:470–8.
4. Najeeb S, Zafar M, Khurshid Z, Siddiqui F. Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. *J Prosthodont Res* 2016;**60**:12-9.
5. Costa-Palau S, Torrents-Nicolas J, Brufau-de Barbera M, Cabratosa-Termes J. Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: a clinical report. *J Prosthet Dent* 2014;**112**:680–2.
6. Ierardo G, Luzzi V, Lesti M, Vozza I, Brugnoletti O, Polimeni A, Bossù M. Peek polymer in orthodontics: A pilot study on children. *J Clin Exp Dent*. 2017;**9**:e1271-5.
7. Adler S, Kistler S, Kistler F , Lermer, J Neugebauer J. Compression-molding rather than milling. A wealth of possible applications for high-performance polymers. *Quintessenz Zahntech* 2013;**39**:2–10.
8. Rzanny A, Gobel F, Fachet M. BioHPP summary of results for material tests. Research Report. Jena, Germany University of Jena, Department of Materials and Technology; 2013.
9. Liebermann A, Wimmer T, Schmidlin P, Scherer H, Löffler P, Roos M, *et al.* Physicomechanical characterization of polyetheretherketone and current esthetic dental CAD/CAM polymers after aging in different storage media. *J Prosthet Dent* 2016;**115**:321-8.
10. Siewert B, Parra M. A new group of material in dentistry. PEEK as a framework material used in 12 piece implant-supported bridges. *Z ZahnärztlImplantol* 2013;**29**:148-59.
11. Skinner H. Composite technology for total hip arthroplasty. *Clin Orthop* 1988;**235**:224–36.
12. Lee W, Koak J, Lim Y, Kim S, Kwon H, Kim M. Stress shielding and fatigue limits of poly-ether-ether-ketone dental implants. *J Biomed Mater Res Part B: Appl Biomater* 2012;**100**:1044–52.
13. Staines M, Robinson W, Hood J. Spherical indentation of tooth enamel. *J Mater Sci* 1981;**16**:2551–6.
14. Rees J, Jacobsen P. The elastic moduli of enamel and dentine. *Clin Mater* 1993;**14**:35–9.
15. Andrikopoulou E, Zoidis P, Artopoulou I, Doukoudakis A. Modified PEEK Resin Bonded Fixed Dental Prosthesis for a Young Cleft Lip and Palate Patient. *J Esthet Restor Dent* 2016;**28**:201-7.
16. Zok F, Miserez A**.** Property maps for abrasion resistance of materials. *Acta Mater* 2007;**55**:6365–71.
17. Wimmer T**,** Huffmann A**,** Eichberger M**,** Schmidlin P**,** Stawarczyk B. Two-body wear rate of PEEK, CAD/CAM resin composite and PMMA: Effect of specimen geometries, antagonist materials and test set-up configuration. *Dent Mater* 2016;**32**:127-36.
18. Schwitalla A, Spintig T, Kallage I, Müller W**.** Flexural behavior of PEEK materials for dental application. *Dent Mater* 2015;**31**:1377-84.
19. Maekawa M, Kanno Z, Wada T, Hongo T, Doi H, Hanawa T, Takashi Ono T, Uo M. Mechanical properties of orthodontic wires made of super engineering plastic. *Dent Mater J* 2015;**34**(1):114–119.

20. Sandler J, Werner P, Shaffer M, Demchuk V, Altstädt V, Windle A. Carbon-nanofibre-reinforced poly(ether ether ketone) composites. *Compos Part A: Appl Sci Manuf* 2002;**33**:1033–9.
21. Martin R, Ishida J. The relative effects of collagen fiber orientation, porosity, density, and mineralization on bone strength. *J Biomech* 1989;**22**:419–26.
22. Sano H, Ciucchi B, Matthews W, Pashley D. Tensile properties of mineralized and demineralized human and bovine dentin. *J Dent Res* 1994;**73**:1205–11.
23. Cavalli V, Giannini M, Carvalho R. Effect of carbamide peroxide bleaching agents on tensile strength of human enamel. *Dental Mater* 2004;**20**:733–9.
24. Williams D, McNamara A, Turner R. Potential of polyetheretherketone (PEEK) and carbon-fibre-reinforced PEEK in medical applications. *J Mat Sci Letters* 1987;**6**:188–190.
25. Wenz L, Merritt K, Brown S, Moet A, Steffee A. In vitro biocompatibility of polyetheretherketone and polysulfone composites. *J Biomed Mater Res* 1990;**24**:207–15.
26. Petillo O, Peluso G, Ambrosio L, Nicolais L, Kao W, Anderson J. *In vivo* induction of macrophage Ia antigen (MHC class II) expression by biomedical polymers in the cage implant system. *J Biomed Mater Res* 1994;**28**:635–46.
27. Hunter A, Archer C, Walker P, Blunn G. Attachment and proliferation of osteoblasts and fibroblasts on biomaterials for orthopaedic use. *Biomaterials* 1995;**16**:287–95.
28. Morrison C, Macnair R, MacDonald C, Wykman A, Goldie I, Grant M. In vitro biocompatibility testing of polymers for orthopaedic implants using cultured fibroblasts and osteoblasts. *Biomaterials* 1995;**16**:987–92.
29. Cook S, Rust-Dawicki A. Preliminary evaluation of titanium-coated PEEK dental implants. *J Oral Implantol* 1995;**21**:176–81.
30. Lin T, Corvelli A, Frondoza C, Roberts J, Hungerford D. Glass peek composite promotes proliferation and osteocalcin production of human osteoblastic cells. *J Biomed Mater Res* 1997;**36**:137–44.
31. Katzer A, Marquardt H, Westendorf J, Wening JV, von Foerster G. Polyetheretherketone -cytotoxicity and mutagenicity in vitro. *Biomaterials* 2002;**23**:1749–59.
32. Najeeb S, Bds ZK, Bds SZ, Bds MS. Bioactivity and Osseointegration of PEEK Are Inferior to Those of Titanium: A Systematic Review. *J Oral Implantol* 2016;**42**:512-6.
33. Ma R, Tang T. Current strategies to improve the bioactivity of PEEK. *Int J Mol Sci* 2014;**15**:5426-45.
34. Zheng Y, Xiong C, Zhang S, Li X, Zhang L. Bone-like apatite coating on functionalized poly(etheretherketone) surface via tailored silanization layers technique. *Mater Sci Eng C Mater Biol Appl* 2015;**55**:512-23.
35. Wolff, J. Das Gesetz der Transformation der Knochen. A. Hirschwald: Berlin, 1892. Trans-lated by Manquet, P. and Furlong, R. as The Law of Bone Remodelling. Springer: Berlin, 1986.
36. Huiskes, R, Ruimerman, R, Van Lenthe, GH, Janssen, JD. Effects of mechanical forces on maintenance and adaptation of form in trabecular bone. *Nature* 2000;**405**:704–706.
37. Brown, IW, Ring, PA. Osteolytic changes in the upper femoral shaft following porous-coated hip replacement. *J Bone Joint Surg Br* 1985;**67**:218–221.
38. Kerner, J, Huiskes, R, van Lenthe, GH, Weinans, H, van Rietbergen, B, Engh, CA, Amis, AA. Corre-lation between pre-operative periprosthetic bone density and post-operative bone loss in THA can be explained by strain-adaptive remodeling. *J Biomech* 1999;**32**:695–703.
39. Lee WT, Koak JY, Lim YJ, Kim SK, Kwon HB, Kim MJ. Stress shielding and fatigue limits of poly-ether-ether-ketone dental implants. *J Biomed Mater Res B Appl Biomater*. 2012;**100**:1044-52.
40. Najeeb S, Khurshid Z, Matinlinna J, Siddiqui F, Nassani M, Baroudi K. Nanomodified Peek Dental Implants: Bioactive Composites and Surface Modification-A Review. *Int J Dent* 2015;**2015**:381759.
41. Durham J, Allen M, Rabiei A. Preparation, characterization and in vitro response of bioactive coatings on polyether ether ketone. *J Biomed Mater Res B Appl Biomater* 2017;**105**:560-7.
42. Shimizu T, Fujibayashi S, Yamaguchi S, Yamamoto K, Otsuki B, Takemoto M, *et al.* Bioactivity of sol-gel-derived TiO2 coating on polyetheretherketone: *In vitro* and *in vivo* studies. *Acta Biomater* 2016;**35**:305-17.
43. Ajami S, Coathup M, Khoury J, Blunn G. Augmenting the bioactivity of polyetheretherketone using a novel accelerated neutral atom beam technique. *J Biomed Mater Res B Appl Biomater* 2016;**105**:1438-46.
44. Ma R, Yu Z, Tang S, Pan Y, Wei J, Tang T. Osseointegration of nanohydroxyapatite- or nano-calcium silicate-incorporated polyetheretherketone bioactive composites *in vivo. Int J Nanomedicine* 2016;**11**:6023-33.
45. Poulsson A, Eglin D, Zeiter S, Camenisch K, Sprecher C, Agarwal Y, *et al.* Osseointegration of machined, injection molded and oxygen plasma modified PEEK implants in a sheep model. *Biomaterials* 2014;**35**:3717-28.
46. Mahjoubi H, Buck E, Manimunda P, Farivar R, Chromik R, Murshed M, Cerruti M. Surface phosphonation enhances hydroxyapatite coating adhesion on polyetheretherketone and its osseointegration potential *Acta Biomater* 2017;**47**:149-58.
47. Wiesli M, Özcan M. High-Performance Polymers and Their Potential Application as Medical and Oral Implant Materials: A Review. *Implant Dent* 2015;**24**:448-57.
48. Maldonado-Naranjo L,. Healy A, Kalfas H. Polyetheretherketone (PEEK) intervertebral cage as a cause of chronic systemic allergy: a case report. *The Spine Journal* 2015;**15**:1-3.
49. Sinha N, Gupta N, Mahendranadh Reddy K, Shastry YM. Versatility of PEEK as a fixed partial denture framework. *J Indian Prosthodont Soc.* 2017;**17**: 80–3.
50. Koutouzis T, Richardson J, Lundgren T. Comparative soft and hard tissue responses to titanium and polymer healing abutments. *J Oral Implantol* 2011;**37**:174–82.
51. Hahnel S, Wieser A, Lang R, Rosentritt M. Biofilm formation on the surface of modern implant abutment materials. *Clin Oral Implants Res* 2015;**26**:1297-301.
52. Rea M, Ricci S, Ghensi P, Lang N, Botticelli D, Soldini C. Marginal healing using Polyetherether ketone as healing abutments: an experimental study in dogs. *Clin Oral Implants Res.* 2017;**28**:46-50.
53. Maté Sánchez de Val J, Gómez-Moreno G, Pérez-Albacete Martínez C, Ramírez-Fernández M, Granero-Marín J, Gehrke S, *et al.* Peri-implant tissue behavior around non-titanium material: Experimental study in dogs. *Ann Anat* 2016; **206**:104-9.
54. Tannous F, Steiner M, Shahin R, Kern M. Retentive forces and fatigue resistance of thermoplastic resin clasps. *Dental Mater* 2012;**28**:273–8.

55. Zoidis P**,** Papathanasiou I**,** Polyzois G**.** The Use of a Modified Poly-Ether-Ether-Ketone (PEEK) as an Alternative Framework Material for Removable Dental Prostheses. A Clinical Report. *J Prosthodont* 2016;**25**:580-4.
56. Zoidis P. Polyetheretherketone Overlay Prosthesis over High Noble Ball Attachments to Overcome Base Metal Sensitivity: *A Clinical Report. J Prosthodont* 2018;**27**:688-93.
57. Zoidis P, Bakiri E, Papathanasiou I, Zappi A. Modified PEEK as an alternative crown framework material for weak abutment teeth: a case report. *Gen Dent* 2017;**65**:37-40.
58. Reich S, Wichmann M, Nkenke E, Proeschel P. Clinical fit of all-ceramic three-unit fixed partial dentures, generated with three different CAD/CAM systems. *Eur J Oral Sci* 2005;**113**:174–9.
59. Zoidis P, Bakiri E, Polyzois G. Using modified polyetheretherketone (PEEK) as an alternative material for endocrown restorations: A short-term clinical report. *J Prosthet Dent* 2017;**117**:335-9.
60. Wagner C**,** Stock V**,** Merk S**,** Schmidlin P**,** Roos M, Eichberger M, *et al***.** Retention load of telescopic crowns with different taper angles between cobalt-chromium and polyetheretherketone made with three different manufacturing processes examined by pull-off test. *J Prosthodont* 2018;**27**:162-8.
61. Alt V, Hannig M, Wöstmann B, Balkenhol M. Fracture strength of temporary fixed partial dentures: CAD/CAM versus directly fabricated restorations. *Dental Mater* 2011;**27**:339–47.
62. Stawarczyk B, Ender A, Trottmann A, Özcan M, Fischer J, Hä-mmerle C. Load-bearing capacity of CAD/CAM milled polymeric three-unit fixed dental prostheses: effect of aging regimens. *Clin Oral Investig* 2012;**16**:1669–77.
63. Stawarczyk B, Eichberger M, Uhrenbacher J, Wimmer T, Edelhoff D, Schmidlin P. Three-unit reinforced polyetheretherketone composite FDPs: influence of fabrication method on load-bearing capacity and failure types. *Dent Mater J* 2015;**34**:7–12.
64. Beuer F, Steff B, Naumann M, Sorensen J. Load-bearing capacity of all-ceramic three-unit fixed partial dentures with different computer-aided design (CAD)/computer- aided manufacturing (CAM) fabricated framework materials. *Eur J Oral Sci* 2008;**116**:381–6.
65. Kolbeck C, Behr M, Rosentritt M, Handel G. Fracture force of tooth–tooth-and implant–tooth-supported all-ceramic fixed partial dentures using titanium vs customised zirconia implant abutments. *Clin Oral Implants Res* 2008;**19**:1049–53.
66. Zoidis P, Papathanasiou I. Modified PEEK resin-bonded fixed dental prosthesis as an interim restoration after implant placement. *J Prosthet Dent* 2016;**116**:637-41.
67. Sproesser O, Schmidlin P, Uhrenbacher J, Roos M, Gernet W, Stawarczyk B. Effect of sulfuric acid etching of polyetheretherketone on the shear bond strength to resin cements. *J Adhes Dent* 2014;**16**:465–72.
68. Keul C, Liebermann A, Schmidlin P, Roos M, Sener B, Stawarczyk B. Influence of PEEK surface modification on surface properties and bond strength to veneering resin composites. *J Adhes Dent* 2014;**16**:383–92.
69. Zhou L**.,** Qian Y**.,** Zhu Y**.,** Liu H**.,** Gan K**.,** Guo J**.** The effect of different surface treatments on the bond strength of PEEK composite materials. *Dent Mater* 2014; **30**:209-15.
70. Kern M, Lehmann F**.** Influence of surface conditioning on bonding to polyetherketon (PEEK). *Dental Mater* 2012;**28**:1280-3.
71. Uhrenbacher J, Schmidlin P, Keul C, Eichberger Roos M, Gernet W, *et al*. The effect of surface modification on the retention strength of polyetheretherketone crowns adhesively bonded to dentin abutments. *J Prosthet Dent* 2014;**112**:1489–97.
72. Stawarczyk B, Beuer F, Wimmer T, Jahn D, Sener B, Roos M, *et al.* Polyetheretherketone—a suitable material for fixed dental prostheses? J Biomed Mater Res Part B: *Appl Biomater* 2013;**101**:1209–16.
73. Stawarczyk B, Thrun H, Eichberger M, Roos M, Edelhoff D, Schweiger J, te al. Effect of different surface pretreatments and adhesives on the load-bearing capacity of veneered 3-unit PEEK FDPs. *J Prosthet Dent* 2015; **114**:666-73.
74. Heimer S, Schmidlin P**,** Stawarczyk B**.** Discoloration of PMMA, composite, and PEEK. *Clin Oral Investig* 2017;**21**:1191-1200.
75. Heimer S, Schmidlin P, Stawarczyk B. Effect of different cleaning methods of polyetheretherketone on surface roughness and surface free energy properties. *J Appl Biomater Funct Mater* 2016;**14**:248-55.
76. Sturz C, Faber F, Scheer M, Rothamel D, Neugebauer J. Effects of various chair-side surface treatment methods on dental restorative materials with respect to contact angles and surface roughness. *Dent Mater J* 2015;**34**:796-813.