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A Review of PEEK Polymer's Properties and its Use in Removable Prosthesis

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بِسْمِ اللّٰهِ الرَّحْمٰنِ الرَّحِیْمِ

((وَقُلْ رَبِّ زِدْنِيْ عِلْمًا))

صدق الله العظيم

Certification of the Supervisor

I certify that this project entitled “**A review of PEEK polymer’s properties and its use in removable prosthesis**” was prepared by **Murtadha Talib Naïf** under my Supervision at the College of Dentistry/University of Baghdad in partial fulfilment of the graduation requirements for the Bachelor Degree in Dentistry.

Supervisor’s name: Assist. Lec. Moamin Ibrahim Date: 20/4/2023

Dedication

I dedicate this project to my mother, you are my pillar, my strength, and my constant source of encouragement. Your unwavering love and support have made all the difference in my life, and I could not have done this without you. This research is a tribute to your boundless love and the sacrifices you have made for our family.

To the memory of my father I will always be grateful for everything you did for me. Even though you are no longer with us, your memory lives on in my heart and in everything I do. Your words of wisdom continue to guide me, and I am forever grateful for the time we spent together.

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- Murtadha Talib Naïf

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List of Abbreviations

PEEK	Polyetherketoneketone
PAEK	polyaryletherketone
CAD	Computer-aided design
CAM	computer-aided manufacturing
BioHPP	Bio High Performance Polymer
FRC	fiber reinforced composite
N-Zr	nano-zirconia
PMMA	Polymethyl methacrylate
RPD	Removable partial denture
FDP	Fixed dental prosthesis
CoCrMo	cobalt-chrome-molybdenum
RDP	Removable dental prosthesis
CoCr	Cobalt chrome

Introduction

The PEEK (Polyetherketoneketone) emerged in the late 1990s as a semi-crystalline material and showed excellent biological, mechanical, and physical properties for biomedical applications (Zoidis et al., 2016; Amornvit et al., 2019). Promising applications of PEEK biomaterial are dental implant (Najeeb et al., 2016), temporary abutment, fixed prosthesis, removable denture (Sakihara et al., 2019), and finger prosthesis (Wang et al., 2017).

Polyetheretherketone (PEEK) is a semicrystalline thermoplastic biomaterial with a chemical formula of $(-C_6H_4-O-C_6H_4-O-C_6H_4-CO-)_n$. It is one of the Polyaryletherketones (PAEKs) polymer group family, which is characterized by ultra-high molecular weight polyethylene (UHMWPE) (Reinhart and Clements, 1993; Merrett et al., 2002; Callister and Rethwisch, 2007).

It has increasingly employed in industry and as a biomaterial that can be used for medical purposes (Kurtz, 2012; Li et al., 2017) and has attracted more interest than any other implantable material for medical devices in the last 20 years (Rae et al., 2007; Koutouzis et al., 2011; Hahnel et al., 2015; Lee et al., 2017).

PEEK available for medical purposes as granules to be pressed and blank disks to mill. Exceptional solvent resistance, low modulus of elasticity, and biocompatibility with bone make this polymer a good candidate to replace the use of metals in the body (Brillhart and Botsis, 1994; Sobieraj and Rimnac, 2012).

Introduction

PEEK is a thermoplastic polymer that exhibits high levels of durability when subjected to chemical and thermal loads, as well as biocompatibility and superior mechanical properties, making it an excellent candidate for use as an alternative to the conventional resins in the dental field for the fabrication of oral and maxillofacial prosthetics (Kurtz, 2019).

The PEKK and polyetheretherketone (PEEK) are the two most well-known of the polyaryletherketone (PAEK) family. The PAEK family are thermoplastic polymers and have been in the engineering field since the 1980s and shows excellent mechanical properties and chemical resistance (Kurtz and Devine, 2007).

Polyetheretherketone (PEEK) has recently emerged as the material of choice when it comes to high performance polymers, but PEEK may not be the best option for dental applications, where esthetic and long-term structural properties are of the utmost importance. This is because PEEK's performance is constrained by its crystalline structure, and the intricate manufacturing process necessitates high accuracy.. (Shetty et al.2018)

Aims of the review

1. Investigate the literature about different properties of PEEK polymer
2. Evaluate the use of PEEK polymer as a potential replacement for metal framework of removable partial denture

Review of literature

1. History of PEEK

PEEK is a semi-crystal high performance thermoplastic of the poly-aryl family, It was first introduced in the market by ICI (**Imperial Chemical Industries**) in 1981, under the trade name of Victrex® PEEK for industry application. (**Kurtz & Devine, 2007**).

In manufacture of aircraft, turbine blades, piston parts, cable insulation (**Ortega *et al.*, 2017**). The medical grade of PEEK arrived in 1998 and is marketed as PEEK OPTIMAM by Invibio Ltd. (Thornton-Cleveleys, Lancashire, UK) which is a subsidiary of Victrex plc. (**Kurtz & Devine, 2007**).

In comparison, the two grades of PEEK are virtually identical in properties; the only difference is the level of cleanness required during synthesis and fabrication. PEEK-OPTIMATM is synthesised in a clean room production environment, under a higher quality control system. Thus, the quality and purity of the material is ensured for long-term implantation (**Kurtz, 2012**).

Polymers being one of the essential materials in dentistry, poses excellent physical, mechanical properties and are reported to have excellent biocompatibility. Various removable appliances, restorations, and denture base materials are fabricated from polymers (**Xu et al., 2017; Rokaya et al., 2018**).

Polyetherketoneketone (PEKK) is a new polymeric material that has attracted the attention of researchers because of its excellent properties that can be used in many applications (**Najeeb et al., 2016**).

The PEKK is a methacrylate-free thermoplastic high-performance material (**Choupin, 2017**).

PEKK was firstly introduced by Bonner in 1962 (**Huang et al., 2014**), and since then, it has been used for different industrial and military purposes (**Stawarczyk et al., 2015**). Recently, PEKK has increasingly used as a biomaterial with properties suitable for dental and medical applications (**Sorte et al., 2017**).

The PEKK and polyetheretherketone (PEEK) are the two most well-known of the polyaryletherketone (PAEK) family. The PAEK family are thermoplastic polymers and have been in the engineering field since the 1980s and shows excellent mechanical properties and chemical resistance (**Kurtz and Devine, 2007**).

PAEK family show ultra-high performance (superior mechanical performances with chemical resistant) among all thermoplastic composites linked to their processing parameters (**Choupin, 2017**).

1.1 Polymer

The definition of polymer has its origins in the Greek, *polumeres*, meaning “having many parts.” The repeating units (monomers) of a polymer can all be the same, the resulting material is classified as homopolymer. When two or more different monomers are used, the resulting material is classified as a copolymer. However, PEEK is a homopolymer (**Kurtz, 2012**).

1.1.1 PEEK

POLY(ETHERETHERKETONE): acronym is PEEK; a member of the PAEK family; a highly ordered, flexible, resilient, shape-stable, biocompatible polymer machined to final shape, used for removable partial denture frameworks and implant components (**GPT.9, 2017**).

PEEK is a dominant of the PAEK (poly-aryl-ether-ketone) polymer family, which has high-temperature stability (exceeding 300 °C) and high mechanical and chemical resistance. It will be a primary substitute for metallic components in the field of orthopedics and trauma (Kurtz SM *et al.*, 2007).

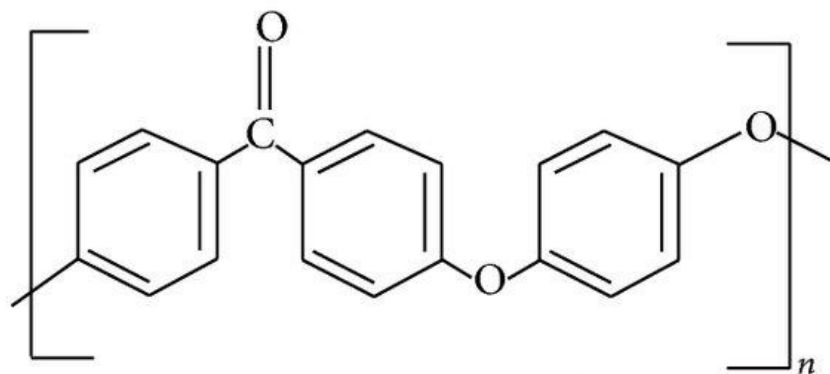
1.1.2 PEEK structure

PEEK is a methacrylate-free polymer. It consists of aromatic benzene molecules connected alternately by functional ketone or ether groups (Stawarczyk *et al.*, 2014).

It is classified as a linear homopolymer, i.e., the same molecule with no branching. The molecular chain of PEEK may be seen as a very long strand of spaghetti, reaching hundreds of meters in length (Kurtz, 2012).

The molecular backbone of PEEK is composed of aromatic rings, with combinations of ketone (–CO–) and ether (–O–) functional groups between them (Figure 1) (Andreiotelli *et al.*, 2009).

These aromatic (benzene) rings are responsible for PEEK stiffness (Figure 2), as they limit the vibration and rotation of its molecular chain, which could have resulted from thermal or mechanical energies; on the other hand, it is free to rotate about the ether (–O–) bonds and ketone-carbon bonds (–CO–) in the axial direction (Kurtz, 2012)



Chemical structure of PEEK

Figure 1: Chemical structure of polyetheretherketone (Kurtz & Devine, 2007).

1.2 PEEK Processing

PEEK is known for its chemical inertness; it is insoluble in all conventional solvents at room temperature. Inertness and insolubility are desirable characteristics of a polymer; however, these limit synthesizing and manufacturing PEEK. It is always considered a challenge to synthesize and convert PEEK into implants (**Kurtz, 2019**).

PEEK processing may involve injection molding, machining from extruded rods, compression-molded sheets, and additive manufacturing like fused deposit modeling (**Haleem and Javaid, 2019**).

PEEK shows lower deformations and higher fracture loads when processed by CAD/CAM than can be achieved by other processes. The fact that this material shows excellent milling and grinding properties can expand the field of indications for PEEK and highlights its potential in dentistry (**Stawarczyk et al., 2015**).

It is more economical for prototype designs to use machining to form components. Highly efficient cutting tools such as carbide or diamond burs are advised because of the excellent mechanical properties (**Kurtz, 2019**).

Using CAD/CAM means higher flexibility in designing and manufacturing medical devices allowing medical device manufacturers broad design and manufacturing flexibility (**Toth et al., 2006**).

More aesthetic material like composite should be used for coating to get an aesthetic result. In literature many surface conditioning methods of PEEK are offered to improve bonding with resin composite crowns. Air abrasion with and without silica coating creates wettable surface, but etching with sulfuric acid makes rough and chemically processed surface (**Najeeb et al., 2016**).

Low energy of PEEK surface creates resistance to chemical processing. **Uhrenbacher *et al.*, (2014)** investigated the modification of the surface strength of PEEK crowns adhesively bonded to dentin abutments. The highest values were found for the airborne-particle abrasion and sulfuric etched groups, and crowns adhesively pretreated with Signum PEEK bond and "visio.link" adhesive system. The results of **Hallmann *et al.*** research show that abraded PEEK surface with 50 µm alumina particles followed by etching with piranha solution lead to the highest tensile bond strength when Heliobond was used as adhesive (**Hallmann *et al.*, 2012**).

All these investigations confirm that resin composites can be used as a covering material of the PEEK frames. However, it is dangerous to use concentrated sulfuric acid in clinical practice.

1.3 PEEK properties

PEEK is quite new material in prosthodontics. Comparing to the metals used in dentistry, PEEK is more aesthetic, stable, biocompatible, lighter and has reduced degree of discoloration (**Tannous *et al.*, 2012; Hallmann *et al.*, 2012**).

This makes it more attractive to patients with high aesthetic requirements. However, due to its grayish brown color PEEK is not suitable for monolithic aesthetic restorations of anterior teeth (**Stawarczyk *et al.*, 2013**).

Mechanical properties of the PEEK are similar to dentin and enamel. Thus it has superiority over metal alloys and ceramic restorations. CAD-CAM milled PEEK fixed prostheses' resistance to fracture is 2354N. It has higher resistance than lithium disilicate ceramic (950 N), aluminium (851 N) or zirconia (981-1331 N) (**Stawarczyk *et al.*, 2015**).

However, there are no clinical data about PEEK's abrasion with other materials such as metal alloys, ceramics, dentin or enamel. Mastication cyclically loads the teeth with a 400 N force. As PEEK has high fracture load resistance it is suitable for producing frames. High fracture resistance is also stated in **Stawarczyk *et al*, (2015)** publications. A mean fracture relative load was 1383 N of 3-unit PEEK frameworks without veneering (**Stawarczyk *et al.*, 2013**).

Despite high fracture resistance, PEEK is relatively weak mechanically in homogenic form. **Tannous *et al*, (2012)** in vitro research showed that clasps made of PEEK have lower resistance forces than the ones made from cobalt-chrome. Scientists have searched for combinations with other materials, to improve PEEK's properties. Modified PEEK containing 20% ceramic fillers known as BioHPP (Bredent GmbH Senden, Germany) is non allergic and has high biocompatibility. Possibility of corrections, excellent stability, great optimal polishable properties and aesthetic white shade of BioHPP help to produce high-quality prosthetic restorations (**Najeeb *et al.*, 2016**).

BioHPP has a great potential as framework material. This is a good alternative to Cr-Co frames for the patients with high aesthetic requirements. But in clinical situations the results might be different Individual abutments on implants can be milled of PEEK. They are usually used for temporary restorations. Randomizedcontrolled clinical trial showed, that there is no statistically significant difference between PEEK and titanium abutments, causing bone resorption or inflammation. Moreover, the attachment of oral microorganisms to PEEK abutments is comparable to those made of titanium, zirconia and poly methyl methacrylate. Therefore, PEEK is a promising alternative to titanium abutments. Comparing to titanium, the polymer could exhibit less stress shielding, but very limited inherent osteoconductive properties (**Najeeb *et al.*, 2016**).

This leads to negative impact in osseointegration process. Nowadays, there are many combinations of PEEK with other materials such as fibers, carbon or ceramics. Due to complexed chemical structure and poor wetting capabilities of PEEK it is hard to prepare its surface in order to increase bond strength and bonding with composites. For good functioning, the surface of PEEK restorations has to be covered by other material like resin composites or lithium disilicate. The best surface processing option is still not found. Moreover, composite as a coating material of the PEEK may degrade with time. So if the polymer frame remains stable, it is necessary to renew the coating material. These are extra expenses to the patient. Unfortunately, there was not enough clinical research made to prove PEEK's superiority over other materials. There is still not enough information stated about complications, biofilm formation on PEEK surface and its resistance to compression. Even so, PEEK is being used in manufacturing fixed restorations (**Uhrenbacher *et al.*, 2014**), dental implants, individual abutments, removable prostheses and their parts and even maxillary obturator prostheses (**Costa-Palau *et al.*, 2014**).

1.4 PEEK in dentistry

Polyetheretherketone (PEEK) is a synthetic, tooth colored polymeric material (**Pokorny D *et al.*, 2010**). PEEK represents a possible alternative to traditional metals in dentistry (**Schwitalla *et al.*, 2015**), considering its improved mechanical properties, biocompatibility, high-temperature stability, electrical non-conductivity, lower hypersensitivity, and allergic reactions, low plaque accumulation, radiolucency, and its resistance to almost all organic and inorganic chemicals (**Çulhaoğlu *et al.*, 2020**).

It was found to provide a more natural feel to the patient combined with efficient performance due to its lesser weight than other traditional metals (**Najeeb *et al.*, 2016**).

Finally, the radiolucent nature of PEEK reduces imaging artifacts **(Schwitalla and Müller, 2013)**.

PEEK is currently used for the manufacturing of temporary abutments, implant-supported bars, and implants. This means fabricating metal-free restorations that are radiolucent, with good biological properties, and acceptable dimensional stability **(Çulhaoğlu et al., 2020)**.

PEEK can be used to make fixed crowns and bridges, removable dental prosthesis and its components, obturators, occlusal splints, intraradicular posts, healing implant abutment, superstructure, or implant body **(Papathanasiou et al., 2020)**. In orthodontics, PEEK has already been tested as a fixed space maintainer **(Ierardo et al., 2017)**.

Moreover, PEEK can also be used as an esthetic wire for orthodontic. **(Maekawa et al., 2015)**.

Due to these unique physical and mechanical properties, PEEK is a promising material for dental applications. The potential of PEEK for various dental applications has been shown in (Figure 3).

1.5 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.

1.5.1 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 polyaryletherketones. 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 fixed dental prosthesis (FDPs) within minutes (Çulhaoğlu *et al.*, 2020).

1.5.2 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 (Uhrenbacher *et al.*, 2014).

1.6 PEEK as removable prosthesis material

Computer-aided design and computer-aided manufacturing (CAD-CAM) techniques can be also used to fabricate RDP frameworks. A previous clinical report has suggested PEEK frameworks combined with acrylic resin denture teeth and heat-cured acrylic resin denture bases as an alternative to conventional Co-Cr frameworks (Harb *et al.*, 2019).

PEEK presents favorable properties such as excellent biocompatibility, good mechanical properties, good thermal and chemical resistance, white color and low specific weight that permit the fabrication of lighter metal-free RPDs eliminating the esthetically unacceptable display of metal clasps and the risk for metallic taste and allergies of conventional RDP metal frameworks (Zoidis *et al.*, 2016).

Another study described the use of milled PEEK frameworks for the fabrication of a removable maxillary obturator prosthesis. Both studies reported high patient satisfaction with regard to esthetics, retention and comfort (Costa-Palau *et al.*, 2014).

Due to its high elasticity, PEEK could reduce stresses and distal torque on the abutment teeth during function (**Zoidis *et al.*, 2016**). In agreement with this statement, a three-dimensional finite element analysis of Chen *et al.* found that PEEK frameworks caused lower stress values on periodontal ligament than cobalt-chromium and Ti-6Al4 V alloy. Thus, PEEK RPDs could be recommended for patients with poor periodontal conditions (**Chen *et al.*, 2019**).

However, in the same study, it was found that PEEK caused the highest stresses on the mucosa and the greatest displacement on the free-end that could lead to pain, advanced bone resorption, denture base failure and compromised chewing efficiency (**Chen *et al.*, 2019**).

The authors concluded that PEEK should be used with caution in distal extension RDPs. Moreover, compared to metal frameworks, PEEK ones showed significantly lower internal stresses.

Retention force and fatigue resistance are crucial factors for RDP clasps. Two in vitro studies found that PEEK clasps exhibited lower retentive force than Co-Cr alloy clasps (**Tribst *et al.*, 2020**).

However, retention force values of PEEK clasps were considered sufficient for clinical use, while Tannous *et al.* recommended the use of 0,5 mm undercuts (**Tannous *et al.*, 2012**).

No significant differences were found in deformation of PEEK and metal clasps after fatigue testing (**Peng *et al.*, 2020**). On the other side, Tribst *et al.* claimed that PEEK should not be used for clasp fabrication because stress values during removal of clasps with higher undercuts are higher than the material strength (**Tribst *et al.*, 2020**).

With respect to fabrication method of PEEK frameworks, milled PEEK clasps demonstrated higher retentive force than thermo-pressed ones. Both

milled and thermo-pressed PEEK clasps showed higher retaining forces at deeper undercuts with a thicker clasp design than Co-Cr clasps after 3 years of fatigue simulation (**Muhsin *et al.*, 2018**).

CAD-CAM PEEK RDP frameworks can be fabricated by several methods such as direct milling of PEEK blanks or 3D printing of a resin/wax pattern framework which is then thermo-pressed using the conventional lost-wax/resin technique (**Negm *et al.*, 2019**).

Clinically acceptable fit values were found for both techniques but directly milled PEEK frameworks had higher fit and trueness values than indirectly fabricated frameworks. In agreement with this result, Arnold *et al.* found that directly milled PEEK RPD frameworks have better precision and fit (43 ± 23 mm horizontal, and 38 ± 21 mm vertical) than cast metal frameworks fabricated using the conventional lost-wax casting technique, indirect rapid prototyping or direct rapid prototyping. This was attributed to the high-quality finish achieved by the milling technique (**Arnold *et al.*, 2018**).

PEEK could also be used as a framework material for complete dentures in order to decrease denture deformation responsible for midline fractures (**Hada *et al.*, 2020**).

However, PEEK frameworks with a thickness of 1 mm could offer only a slight reinforcement to complete dentures, while more rigid materials such as fiber reinforced composite (FRC), nano-zirconia (N-Zr), cobalt-chromium-molybdenum alloy provide greater reinforcement with a thickness of 0,5 mm. This finding can be explained by the similar deformation of PEEK and PMMA due to their comparable elastic moduli which are 4 GPa (**Alexakou *et al.*, 2019**) and 2.7 GPa, respectively. Muhsin *et al.* evaluated denture bases fabricated by milled or thermo-pressed PEEK and PMMA. The results of this in vitro study showed that PEEK denture bases had higher impact and tensile

strength than PMMA. Thus, PEEK could be regarded as a material suitable for denture bases providing resistance to notch concentration and fracture (**Muhsin et al., 2019**). Furthermore, two in vitro studies found better stain resistance and lower surface roughness after polishing of PEEK materials compared with PMMA (**Heimer et al., 2017**).

Furthermore, a few studies stated that PEEK may be used as an attachment retaining implant-supported overdentures (**Spies et al., 2019**). In a clinical study 15 fully edentulous patients were rehabilitated with a maxillary overdenture supported by 4 implants and CAD-CAM fabricated PEEK bar. After a year in function, no implants were lost and an 80% success rate for implant-supported overdentures was found (**Mangano et al., 2019**).

A clinical report also suggested the use of an implant-supported overdenture with the receptor part of the bar milled from PEEK polymerized into a zirconia framework for the rehabilitation of an edentulous patient. The authors reported high patient satisfaction with function and esthetics after 6 months (**Spies et al., 2019**).

PEEK as clasp material and its comparison with metal clasp Clasps can be used as retention elements to attach a prosthesis to the remaining teeth, thus ensuring functional stability during enunciation and mastication. In the course of time, a wide variety of clasps have been designed to tailor to various indications. Clasps traditionally consist of a retentive arm that passes over the prosthetic equator and comes to a rest in an undercut, while the reciprocal arm undertakes the task of opposing lateral forces during insertion and removal (**Davenport et al., 2001**). The depth of the undercut as well as the elastic modulus of the clasp material directly affects the retention of RDPs (**Osada et al., 2012**).

Metal alloy has for a long time been the material of choice for RDP clasps, as its outstanding mechanical properties are well documented

(Mahmoud, 2007). The alloy most commonly used is cobalt-chrome-molybdenum (CoCrMo) (Kola *et al.*, 2016).

Numerous studies have observed significantly higher retention load values of CoCrMo clasps than seen for alternative materials such as titanium. With ever rising esthetic demands, research activities have focused on tackling the main drawback of alloy clasps: their metallic color (Byron *et al.*, 2007).

One relatively new approach is to manufacture clasps of a tooth-colored thermoplastic material, such as polyoxymethylene, polycarbonate and polyamide, or polyaryletherketone (PAEK) (Tannous *et al.*, 2018).

Micovic *et al.* (2021) conducted a study to examine the retention force of RDP clasps made from different PEEK materials in comparison with a CoCrMo control group after storage in artificial saliva to imitate clinical conditions. When regarding the choice of clasp material, the control group showed superior retention values compared to the three PEEK materials. These results are in line with previous examinations investigating the retentive force and fatigue resistance of both PEEK and CoCr clasps (Peng *et al.*, 2019).

Even though PEEK clasps presented lower values, they might provide enough retention for a clinical usage, as they exceed the suggested retention force of 5–10 N per clasp (Torii *et al.*, 2018).

As excessive retentive forces can overstrain the remaining abutment teeth, especially in periodontally compromised dentitions (Muller *et al.*, 2013), PEEK materials could represent a valid alternative. As all PEEK materials showed similar results over the course of aging, the manufacturing process does not seem to hold an influence on the resulting mechanical properties. As most dental laboratories nowadays have access to high-end milling machines, this elegant process regarded to be less time consuming and prone to manual mistakes should be preferred (Tallarico, 2020).

Artificial aging also presented an impact on the retention force. The control group (CoCrMo clasp) showed a high decrease of its values, while PEEK clasps presented similar results before and after the aging process. A high decrease in the retention force of the control group can be explained by alloy corrosion taking place in wet environments, which has previously been reported to lead to a reduced fatigue strength of CoCr. While the three PEEK materials also presented a decline in retention force, this was not significant. These results are consistent with a previous study investigating the behavior of PEEK during artificial aging with different saliva solutions that reported the thermoplastic to show a great structural stability and little or no impact of varying pH values on its nanomechanical properties (**Gao *et al.*, 2015**).



Fig. 2 RDP clasp specimens made of CoCrMo, PEEKmilled1, PEEKmilled2, and PEEKpressed. (**Gao *et al.*, 2015**).

The repetitive insertion and removal of the clasps led to a reduction of the retention force of PEEKmilled1 and PEEKpressed specimens at all aging levels. For PEEKmilled2 and CoCrMo, an increase of retention force was observed initially, before values decreased with a repetitive insertion and removal of the RDP clasps at the subsequent aging levels. An initial increase in retention force might be explained by abrasion phenomena of both the model and clasps resulting in an improved fit of the clasps and in consequence, an increased retention force. A previous examination investigating the retentive force of thermoplastic resins and cobalt-chrome over a simulation period of 10 years reported similar findings with an initial increase in values during the first period of cycling that was later on substituted by a continuous decrease (**Tannous *et al.*, 2012**).

The elastic modulus plays an important role in fatigue testing, as a material with a high elastic modulus is able to assume its prior structure without permanent deformation. CoCrMo, which possesses a high elastic modulus of 220 GPa (**Al Jabbari, 2014**), should thus in theory be less prone to a decrease in retention force due to a repetitive insertion and removal of the clasps than PEEK, which only holds an elastic modulus of around 4 GPa (**Schwitalla *et al.*, 2015**).

In contrast to this idea, a recent study observed polymer-based clasps to act more consistently over a prolonged aging process, which included cycles of repeated insertion and removal along both ideal and non-ideal paths in artificial saliva, while exhibiting inferior retention forces in comparison to conventional CoCr clasps (**Marie *et al.*, 2019**).

Regarding clinical implications, PEEK materials might therefore represent the material of choice for anterior abutment teeth that possess little anatomical undercut and in consequence require little deformation during insertion and removal, while CoCrMo could be the material of choice for the posterior

regions, where molars provide a large retentive area and high masticatory forces demand superior retentive capacities and functional stability (**Davenport *et al.*, 2001**).

Individual patient situations might thus call for individualized treatment planning regarding the choice of clasp material. Only few reports about PEEK's behavior in clinical conditions are available. According to one recently published case report with a 2-year follow-up period, PEEK shows promising results, as few color and texture changes of PEEK were found macroscopically. The clasp arm still fitted well without any deformation and a high subjective satisfaction was expressed by both the practitioner and the patient (**Ichikawa *et al.*, 2019**).

Further advantages include the low weight of PEEK prostheses, the tooth-similar color, a reportedly good fit and high retention, and a protective effect on the periodontal ligament (**Chen *et al.*, 2019**).

However, the indication of PEEK as a framework material remains controversial, as its stability in a free-end situation under masticatory forces is not conducive for a RDP's stability (**Chen *et al.*, 2019**).

Conclusion

The PEEK materials present suitable physical, mechanical, and chemical properties and can be used for various applications such as restorative material, crown and bridge work, framework material for an implant-supported fixed prosthesis, dental biomaterial implants and removable prosthesis.

The use of CAD/CAM technology for constructing an RPD metal-free framework results in a prosthesis with adequate fit, and good patient satisfaction in terms of function and esthetics. With proper patient selection and treatment planning, milled PEEK can be considered a useful alternative framework material for RPDs.

Further, modifications and improving material properties can result in wider applications in clinical dentistry. Long term evaluations are needed as PEEK is recently applied in dentistry, and there are limited studies available.

References

(A)

- Abu Bakar, M., Cheang, P. and Khor, K. (2003) Mechanical properties of injection molded hydroxyapatite-polyetheretherketone biocomposites. *Composites Science and Technology*, 63(3-4),421-425.
- Adler S, Kistler S, Kistler F, Lermer, J Neugebauer J. (2013) Compressionmolding rather than milling. A wealth of possible applications for highperformance polymers. *Quintessenz Zahntech* 39:2–10. 8.
- Al Jabbari YS. (2014) Physico-mechanical properties and prosthodontic applications of Co-Cr dental alloys: a review of the literature. *J Adv Prosthodont*. 6:138–145.
- Alexakou E, Damanaki M, Zoidis P, Bakiri E, Mouzis N, Smidt G, et al. (2019) PEEK high performance polymers: a review of properties and clinical applications in prosthodontics and restorative dentistry. *Eur J Prosthodont Restor Dent*. 27(3):113–21.
- Amornvit P, Rokaya D, Sanohkan S. (2019) Applications of PEEK in implant retained finger prosthesis. *J Int Dental Med Res* 12:1606–9.
- Andreiotelli, M., Wenz, H. and Kohal, R. (2009) Are ceramic implants a viable alternative to titanium implants? A systematic literature review. *Clinical Oral Implants Research*, 20,32-47.
- Arnold C, Hey J, Schweyen R, Setz JM. (2018) Accuracy of CAD-CAM-fabricated removable partial dentures. *J Prosthet Dent*. 119(4):586–92.

(B)

- Byron R, Jr, Frazer RQ, Herren MC. (2007) Rotational path removable partial denture: an esthetic alternative. *Gen Dent.* 55:245–250.

(C)

- Camarini, E., Tomeh, J., Dias, R. and da Silva, E. (2011) Reconstruction of Frontal Bone Using Specific Implant Polyether-Ether-Ketone. *Journal of Craniofacial Surgery*, 22(6),2205-2207.
- Chen X, Mao B, Zhu Z, Yu J, Lu Y, Zhang Q, et al. (2019) A three-dimensional finite element analysis of mechanical function for 4 removable partial denture designs with 3 framework materials: CoCr, Ti-6Al-4V alloy and PEEK. *Sci Rep.* 9(1):13975.
- Chen X, Mao B, Zhu Z, Yu J, Lu Y, Zhang Q, Yue L, Yu H. (2019) A three- dimensional finite element analysis of mechanical function for 4 removable partial denture designs with 3 framework materials: CoCr, Ti-6Al-4V alloy and PEEK. *Sci Rep.* 9:13975.
- Choupin T. (2017) Mechanical performances of PEKK thermoplastic composites linked to their processing parameters.
- Costa-Palau S, Torrents-Nicolas J, Brufau-de Barberà M, Cabratosa-Termes J. (2014) Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: a clinical report. *The Journal of prosthetic dentistry.* 112(3):680-2.
- Costa-Palau S, Torrents-Nicolas J, Brufau-de Barberà M, Cabratosa-Termes J. (2014) Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: a clinical report. *J Prosthet Dent.* 112(3):680–2.

- Costa-Palau, S., Torrents-Nicolas, J., Brufau-de Barberà, M. and Cabratosa- Termes, J. (2014) Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: a clinical report. *The Journal of prosthetic dentistry*, 112(3),680-682.
- Çulhaoğlu, A. K., Özkır, S. E., Şahin, V., Yılmaz, B. & Kılıçarslan, M. A. (2020) Effect of Various Treatment Modalities on Surface Characteristics and Shear Bond Strengths of Polyetheretherketone-Based Core Materials. *Journal of Prosthodontics*. 29, 136-141.

(D)

- Davenport JC, Basker RM, Heath JR, Ralph JP, Glantz PO, Hammond P. (2001) Clasp design. *Br Dent J*. 190:71–81.

(G)

- Gao S, Gao S, Xu B, Yu H. (2015) Effects of different pH-values on the nanomechanical surface properties of PEEK and CFR-PEEK compared to dental resin-based materials. *Materials (Basel)* 8:4751–4767.
- Garcia-Gonzalez D, Rusinek A, Jankowiak T, Arias A. (2015) Mechanical impact behavior of polyether–ether–ketone (PEEK). *Composite Structures*. 2015; 124:88-99.

(H)

- Hada T, Suzuki T, Minakuchi S, Takahashi H. (2020) Reduction in maxillary complete denture deformation using framework material made by computer- aided design and manufacturing systems. *J Mech Behav Biomed Mater.* 2020;103: 103514.
- Haleem, A. & Javaid, M. (2019) Polyether ether ketone (PEEK) and its manufacturing of customised 3D printed dentistry parts using additive manufacturing. *Clinical Epidemiology and Global Health.* 7, 654-660.
- Hallmann L, Mehl A, Sereno N, Hämmerle CH. (2012) The improvement of adhesive properties of PEEK through different pre-treatments. *Applied Surface Science.* 258(18):7213-8.
- Harb IE, Abdel-Khalek EA, Hegazy SA. (2019) CAD/CAM constructed poly (etheretherketone) (PEEK) framework of Kennedy class I removable partial denture: a clinical report. *J Prosthodont.* 28(2): e595–8.
- Harb, I. E., Abdel-Khalek, E. A., & Hegazy, S. A. (2019) CAD/CAM constructed poly (etheretherketone)(PEEK) framework of Kennedy class I removable partial denture: a clinical report. *Journal of Prosthodontics,* 28(2), e595-e598.
- Heimer S, Schmidlin PR, Stawarczyk B. (2017) Discoloration of PMMA, composite, and PEEK. *Clin Oral Investig.* 2017;21(4):1191–200.
- Huang B, Qian J, Wang G, Cai M. (2014) Synthesis and properties of novel copolymers of poly (ether ketone diphenyl ketone ether ketone ketone) and poly (ether amide ether amide ether ketone ketone). *Polym Eng Sci* 54:1757–64.

(I)

- Ichikawa T, Kurahashi K, Liu L, Matsuda T, Ishida Y (2019) Use of a polyetheretherketone clasp retainer for removable partial denture: *a case report*. 54:1757–64.
- Ierardo, G., Luzzi, V., Lesti, M., Voza, I., Brugnoletti, O., Polimeni, A. & Bossù, M. (2017) Peek polymer in orthodontics: A pilot study on children. *Journal of clinical and experimental dentistry*. 9, e1271-e1275.

(K)

- Katzer, A., Marquardt, H., Westendorf, J., Wening, J. and von Foerster, G., (2002) Polyetheretherketone—cytotoxicity and mutagenicity in vitro. *Biomaterials*, 23(8),1749-1759.
- Kern, M. and Lehmann, F. (2012) Influence of surface conditioning on bonding to polyetheretherketon (PEEK). *Dental Materials*, 28(12), 1280-1283.
- Kola MZ, Raghav D, Kumar P, Alqahtani F, Murayshed MS, Bhagat TV. (2016) In vitro assessment of clasps of cobalt-chromium and nickel-titanium alloys in removable prosthesis. *J Contemp Dent Pract*. 17:253–257.
- Koyama S, Sasaki K, Yokoyama M, et al: (2010) Evaluation of factors affecting the continuing use and patient satisfaction with removable partial dentures over 5 years. *J Prosthodont Res* 54:97-101
- Kurtz, Devine JN. (2007) PEEK biomaterials in trauma, orthopedic, and spinal implants. *Biomaterials* 28:4845–69.

- Kurtz, and Devine, J. (2007) PEEK biomaterials in trauma, orthopedic, and spinal implants. *Biomaterials*, 28(32),4845-4869.
- Kurtz, (2019) PEEK biomaterials handbook. William Andrew.
- Kurtz, (2012) *PEEK biomaterials handbook*. 1st ed. Norwich, N.Y: William Andrew,2.

(M)

- Ma R, Tang T. (2014) Current strategies to improve the bioactivity of PEEK. *International journal of molecular sciences*. 15(4):5426-45.
- Maekawa, M., Kanno, Z., Wada, T., Hongo, T., Doi, H., Hanawa, T., Ono, T. and Uo, M., 2015. Mechanical properties of orthodontic wires made of super engineering plastic. *Dental materials journal*,2014-202.
- Mahmoud A. (2007) Pre-overloading to extend fatigue life of cast clasps. *J Dent Res*. 86:868–872.
- Mangano F, Mangano C, Margiani B, Admakin O. (2019) Combining intraoral and face scans for the design and fabrication of computer-assisted design/ computer-assisted manufacturing (CAD/CAM) polyether-etherketone (PEEK) implant-supported bars for maxillary overdentures. *Scanning*. 2019: 4274715.
- Marie A, Keeling A, Hyde TP, Nattress BR, Pavitt S, Murphy RJ, Shary TJ, Dillon S, Osnes C, Wood DJ. (2019) Deformation and retentive force following in vitro cyclic fatigue of cobalt-chrome and aryl ketone polymer (AKP) clasps. *Dent Mater*. 35: e113–e121.

- Micovic, D., Mayinger, F., Bauer, S., Roos, M., Eichberger, M., & Stawarczyk, B. (2021). Is the high-performance thermoplastic polyetheretherketone indicated as a clasp material for removable dental prostheses?. *Clinical Oral Investigations*, 25(5), 2859-2866.
- Monich PR, Berti FV, Porto LM, Henriques B, de Oliveira APN, Fredel MC et al. (2017) Physicochemical and biological assessment of PEEK composites embedding natural amorphous silica fibers for biomedical applications. *Materials Science and Engineering: C*. 79: 354-62.
- Muller S, Eickholz P, Reitmeir P, Eger T. (2013) Long-term tooth loss in periodontally compromised but treated patients according to the type of prosthodontic treatment. A retrospective study. *J Oral Rehabil*. 40:358–367.

(N)

- Najeeb S, Zafar MS, Khurshid Z, Siddiqui F. (2016) Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. *J Prosthodontic Res* 60:12–9.
- Najeeb S, Zafar MS, Khurshid Z, Siddiqui F. (2016) Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. *Journal of prosthodontic Research*. 60(1):12-9.
- Najeeb, S., Zafar, M.S., Khurshid, Z. and Siddiqui, F. (2016) Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. *Journal of prosthodontic research*, 60(1),12-19.

- Negm EE, Aboutaleb FA, Alam-Eldein AM. (2019) Virtual evaluation of the accuracy of fit and trueness in maxillary poly (etheretherketone) removable partial denture frameworks fabricated by direct and indirect CAD/CAM techniques. *J Prosthodont.* 28(7):804–10.

(O)

- Ortega-Martínez J, Farré-Lladós M, Cano-Batalla J, Cabratosa-Termes J. (2017) Polyetheretherketone (PEEK) as a medical and dental material. A literature review. *Arch Med Res.* May 5(5):01-16.
- Osada H, Shimpo H, Hayakawa T, Ohkubo C. (2013) Influence of thickness and undercut of thermoplastic resin clasps on retentive force. *Dent Mater J.* 32:381–389.

(P)

- Papathanasiou, I., Kamposiora, P., Papavasiliou, G. & Ferrari, M. (2020) The use of PEEK in digital prosthodontics: A narrative review. *BMC Oral Health.* 20, 217.
- Peng TY, Ogawa Y, Akebono H, Iwaguro S, Sugeta A, Shimoe S. (2020) Finiteelement analysis and optimization of the mechanical properties of polyetheretherketone (PEEK) clasps for removable partial dentures. *J Prosthodont Res.* 64(3):250–6.
- Peng TY, Ogawa Y, Akebono H, Iwaguro S, Sugeta A, Shimoe S. (2019) Finite-element analysis and optimization of the mechanical properties of polyetheretherketone (PEEK) clasps for removable partial dentures. *J Prosthodont Res.* 64:250–256.

- Phoenix RD, Cagna DR, DeFreest CF: (2003) Stewart's Clinical Removable Partial Prosthodontics (ed 3). *Chicago, Quintessence*, 19-103.
- Pokorný, D., Fulin, P., Slouf, M., Jahoda, D., Landor, I. and Sosna, A. (2010) Polyetheretherketone (PEEK). Part II: Application in clinical practice. *Acta chirurgiae orthopaedicae et traumatologiae Cechoslovaca*, 77(6),470-478.

(R)

- Rabiei, A. and Sandukas, S. (2013) Processing and evaluation of bioactive coatings on polymeric implants. *Journal of Biomedical Materials Research Part A*, 101A (9),2621-2629.
- Rabiei, A. and Sandukas, S. (2013) Processing and evaluation of bioactive coatings on polymeric implants. *Journal of Biomedical Materials Research PartA*, 101A(9),2621-2629.
- Reitman, M., Jaekel, D., Siskey, R. et al. "Chapter 4: (2012) Morphology and crystalline architecture of polyaryletherketones" In Kurtz S.M. (ed.) PEEK Biomaterial Handbook. *Oxford: William Andrew Publishing*. 49-59
- Rokaya D, Srimaneepong V, Sapkota J, Qin J, Siraleartmukul K, Siriwongrungson V. (2018) Polymeric materials and films in dentistry: an overview. *J Adv Res* 14:25–34.
- Rzanny A, Gobel F, Facht M. (2013) BioHPP summary of results for material tests. Research Report. Jena, Germany University of Jena, Department of Materials and Technology.

• (S)

- Sakihara M, Taira Y, Sawase T. (2019) Effects of sulfuric and vinyl sulfonic acid etchants on bond strength of resin composite to polyetherketoneketone. *Odontology* 107:158–64.
- Schmidlin PR, Stawarczyk B, Wieland M, Attin T, Hammerle CH, Fischer J. (2010) Effect of different surface pretreatments and luting materials on shear bond strength to PEEK. *Dental materials*. 2010;26(6): 553-9.
- Schwitalla A, Muller WD. (2013) PEEK dental implants: a review of the literature. *Journal of Oral Implantology*. 39(6): 743-9.
- Schwitalla AD, Spintig T, Kallage I, Muller WD. (2015) Flexural behavior of PEEK materials for dental application. *Dent Mater*. 31:1377–1384.
- Schwitalla, A. & Müller, W. D. (2013) PEEK dental implants: a review of the literature. *Journal of Oral Implantology*. 39, 743-9.
- Schwitalla, A. D., Spintig, T., Kallage, I. & Müller, W.-D. (2015) Flexural behavior of PEEK materials for dental application. *Dental Materials Journal*. 31,1377-1384.
- Schwitalla, A., Abou-Emara, M., Zimmermann, T., Spintig, T., Beuer, F., Lackmann, J. and Müller, W. (2016) The applicability of PEEK-based abutment screws. *Journal of the Mechanical Behavior of Biomedical Materials*, 63,244-251
- Sheiko N, Kekicheff P, Marie P, Schmutz M, Jacomine L, Perrin-Schmitt F. (2016) PEEK (polyether-ether-ketone)-coated nitinol wire: Film stability for biocompatibility applications. *Applied Surface Science*. 389:651-65.

- Sorte N, Bhat V, Hegde C. (2017) Poly-ether-ether-ketone (PEEK): a review. *Int J Recent Sci Res* 8:19208–11.
- Spies BC, Petsch M, Kohal RJ, Beuer F. (2018) Digital production of a zirconia, implant-supported removable prosthesis with an individual Bar attachment milled from polyether ether ketone: a case history report. *Int J Prosthodont.* 31(5):471–4.
- Stawarczyk B, Beuer F, Wimmer T, Jahn D, Sener B, Roos M et al. (2013) Polyetheretherketone - a suitable material for fixed dental prostheses? *Journal of Biomedical Materials Research Part B: Applied Biomaterials.* 101(7): 1209- 16.
- Stawarczyk B, Eichberger M, Uhrenbacher J, Wimmer T, Edelhoff D, Schmidlin PR. (2015) Three-unit reinforced polyetheretherketone composite FDPs: influence of fabrication method on load-bearing capacity and failure types. *Dent Mater J* 34:7–12.
- Stawarczyk B, Eichberger M, Uhrenbacher J, Wimmer T, Edelhoff D, Schmidlin PR. (2015) Three-unit reinforced polyetheretherketone composite FDPs: Influence of fabrication method on load-bearing capacity and failure types. *Dental materials Journal.* 2015; 34(1): 7-12.
- Stawarczyk, B., Jordan, P., Schmidlin, P. R., Roos, M., Eichberger, M., Gernet, W. & Keul, C. (2014) PEEK surface treatment effects on tensile bond strength to veneering resins. *Journal of Prosthetic Dentistry.* 112, 1278-1288.
- Stawarczyk, B., Thrun, H., Eichberger, M., Roos, M., Edelhoff, D., Schweiger, J. & Schmidlin, P. R. (2015) Effect of different surface pretreatments and adhesives on the load-bearing capacity of veneered 3-unit PEEK FDPs. *Journal of Prosthetic Dentistry.* 114, 666-673.

(T)

- Tallarico M (2020) Computerization and digital workflow in medicine: focus on digital dentistry. *Materials (Basel)* 13.
- Tannous F, Steiner M, Shahin R, Kern M. (2012) Retentive forces and fatigue resistance of thermoplastic resin clasps. *Dental materials*. 28(3):273-8.
- Tannous, F., Steiner, M., Shahin, R. and Kern, M. (2012) Retentive forces and fatigue resistance of thermoplastic resin clasps. *Dental materials*, 28(3),273-278.
- *The Journal of Prosthetic Dentistry*. (2017) *The Glossary of Prosthodontic Terms*. 117(5),C1-e105.
- Torii M, Nakata T, Takahashi K, Kawamura N, Shimpo H, Ohkubo C. (2018) Fitness and retentive force of cobalt-chromium alloy clasps fabricated with repeated laser sintering and milling. *J Prosthodont Res*. 62:342–346.
- Toth, J.M., Wang, M., Estes, B.T., Scifert, J.L., Seim III, H.B. and Turner, A.S. (2006) Polyetheretherketone as a biomaterial for spinal applications. *Biomaterials*, 27(3),324-334.
- Tribst JPM, Dal Piva AMO, Borges ALS, Araújo RM, da Silva JMF, Bottino MA, et al. (2020) Effect of different materials and undercut on the removal force and stress distribution in circumferential clasps during direct retainer action in removable partial dentures. *Dent Mater*. 36(2):179–86.

(U)

- Uhrenbacher J, Schmidlin PR, Keul C, Eichberger M, Roos M, Gernet W. (2014) The effect of surface modification on the retention strength of polyetheretherketone crowns adhesively bonded to dentin abutments. *The Journal of prosthetic dentistry*. 112(6):1489-97.
- Uhrenbacher, J., Schmidlin, P.R., Keul, C., Eichberger, M., Roos, M., Gernet, W. and Stawarczyk, B. (2014) The effect of surface modification on the retention strength of polyetheretherketone crowns adhesively bonded to dentin abutments. *The Journal of prosthetic dentistry*, 112(6),1489-1497.

(V)

- Vaezi M, Yang S. (2015) A novel bioactive PEEK/HA composite with controlled 3D interconnected HA network. *International Journal of Bioprinting*. 1(1): 66-76.

(W)

- Wang M, Bhardwaj G, Webster TJ. (2017) Antibacterial properties of PEKK for orthopedic applications. *Int J Nanomed* 12:6471–6.
- Wenz, L.M., Merritt, K., Brown, S.A., Moet, A. and Steffee, A.D. (1990) In vitro biocompatibility of polyetheretherketone and polysulfone composites. *Journal of biomedical materials research*, 24(2),207-215.

(X)

- Xin H, Shepherd D, Dearn K. (2013) Strength of poly-etherether-ketone: effects of sterilisation and thermal ageing. *Polymer Testing*. 32(6): 1001-1005.
- Xu X, He L, Zhu B, Li J, Li J. (2017) Advances in polymeric materials for dental applications. *Polym Chem* 8:807–23.

(Z)

- Zhou L, Qia Y, Zhu Y, Liu H, Gan K, Guo J. (2014) The effect of different surface treatments on the bond strength of PEEK composite materials. *Dental materials*. (30): e209–e215.
- Zoidis P, Papathanasiou I, Polyzois G. (2015) The Use of a Modified Poly Ether Ether Ketone (PEEK) as an Alternative Framework Material for Removable Dental Prostheses. A Clinical Report. *Journal of Prosthodontics*. 25(7), 580-84.
- Zoidis P, Papathanasiou I, Polyzois G. (2016) The use of a modified poly-etherether-ketone (PEEK) as an alternative framework material for removable dental prostheses. A clinical report. *J Prosthodont*. 2016;25(7):580–4.
- Zoidis P, Papathanasiou I, Polyzois G. (2016) The use of a modified poly-ether-etherketone (PEEK) as an alternative framework material for removable dental prostheses. A clinical report. *J Prosthodont* 25:580–4.