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A review of PEEK polymer's properties and its use in removable prosthesis

The College of Dentistry, University of Baghdad, Department of prosthodontics in Partial Fulfillment for the Bachelor of Dental Surgery

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Dedication

I would like to dedicate this project to my father and my mother, who showed me unconditional love and taught me the values of hardwork and integrity, they are the reason why I am here today.

To my sister, my backbone, my soulmate for being always by my side.

To my beloved fiancé for his endless love, support and encouragement.

To my martians who lifted me up whenever I felt down, they know how to calm me down, keep me smiling, my best cheerleaders, I will alwyas appreciate you.

To my homies who made my days in the university an enjoyable journey and we made amazing memories throughout our journey and I will be forever grateful you are in my life.

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First and foremost, praises and thanks to **God** Almighty for helping me fulfill my dream, for his blessings throughout my work to complete it successfully.

I would like to extend my deepest respect and gratitude to the Dean of College of Dentistry, University of Baghdad, **Prof. Dr. Raghad Al-Hashimi**.

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List of Abbreviations

Abb.	Meaning
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

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). The PEEK 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).

Aims of the review

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

Chapter one: Review of literature

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)

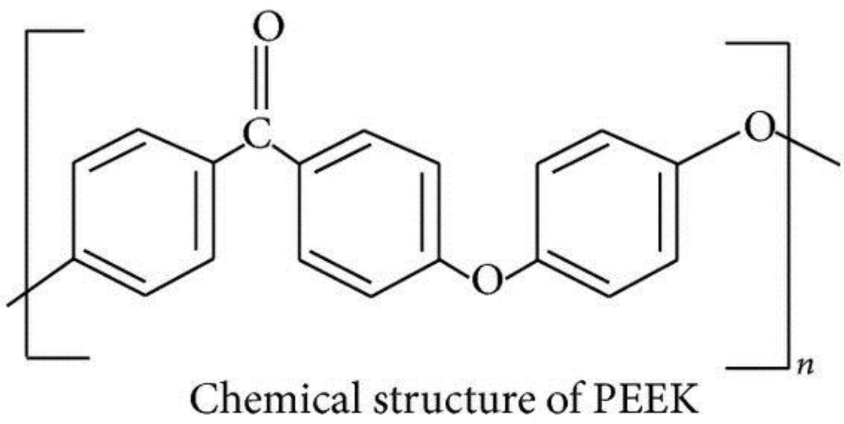

Figure 1: Chemical structure of polyetheretherketone (Kurtz & Devine, 2007).

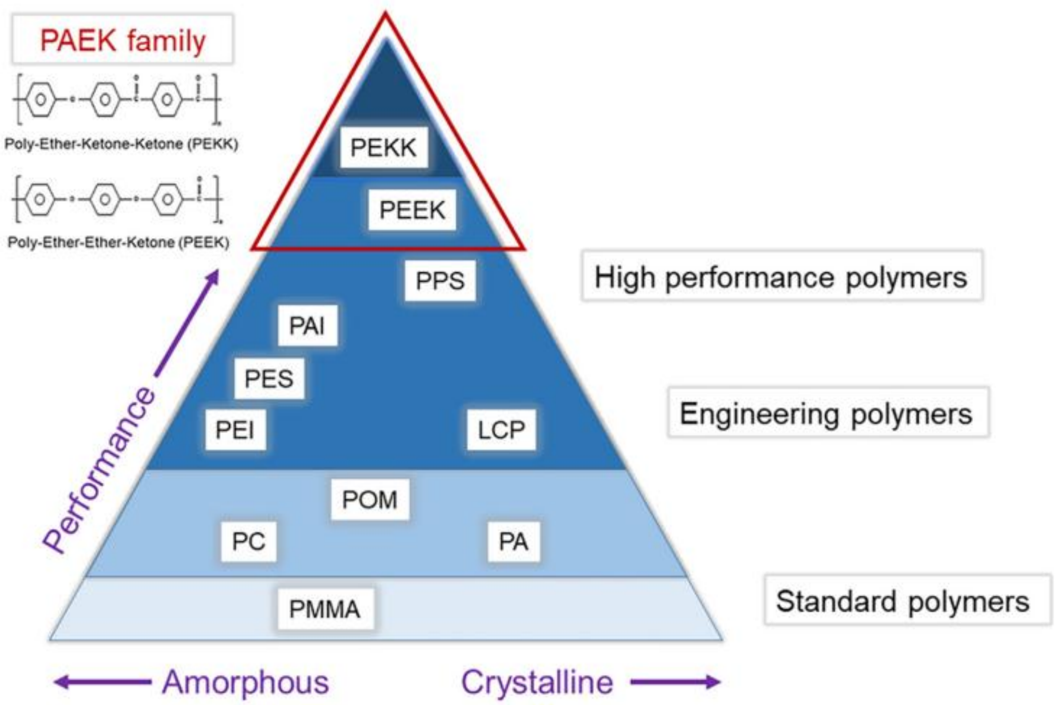

Figure 2: Structure and performance of PAEK (PEKK and PEEK), and fabrication of PEKK.

1.1.3 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).

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 biocompability. 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. Randomized controlled 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 various Characteristics of PEEK are shown in (Table 1-2) (Costa-Palau *et al*., 2014).

Table 1. Characteristics of polyether ether ketone

Author of the article	Year	Properties			Applications of PEEK in prosthodontics
		Mechanical	Chemical	Biological	
Ma R et al.	2014	Elastic modulus~ 8.3 GPa	Resistant to corrosion	Biocompatible	Component parts of implants
Najeeb S et al.	2016	Tensile strength 80 MPa; Young's modulus 3-4 GP; CFR-PEEK 120 MPa	-	Non allergic; Has low plaque affi nity	Implant abutments; Fixed crowns, fi xed bridges; Removable dentures and components
Vaezi M et al.	2015	-	Resistant to hydrolysis	Non allergic; Has low plaque affi nity	Component parts of implants
Zoidis P et al.	2015	-	-	Non allergic; Has low plaque affi nity; Biocompatible	An alternative framework material for removable partial dentures
Garcia-Gonzalez D et al.	2015	Elastic modulus 3.6 GPa; Density 1300 kg/m³	Thermal conductivity 0.29 W/mK	-	Component parts of implants
Sheiko N et al.	2016	-	-	Biocompatible	Component parts of implants
Schmidlin PR et al.	2010	-	-	Biocompatible	Fixed prosthesis: temporary abutment for implants, crowns
Tannous F et al.	2012	Tensile strength 97 MPa; Elastic modulus 4 GPa.	-	-	Partial removable dentures:

					thermoplastic resin clasps
Monich PR et al.	2017	-	The glass transition temperature 143°C; The crystalline melt transition temperature 343 °C	Biocompatible	Component parts of implants
Schwitalla A et al.	2013	Elastic modulus 3,6 GPa; Carbon fi ber–reinforced PEEK (CFR-PEEK) obtain an elastic modulus of 17.4 GPa similar to that of cortical bone	-	-	Component parts of implants
Xin H et al.	2013	Flexural yielding strength 165 MPa; Young's modulus 3.7 GPa	-	-	Component parts of implants
Zhou L et al.	2014	-	-	Biocompatible	Component parts of implants: abutments, healing caps; Fixed protheses.

Table 2. Shear bond strength of PEEK to dental tissues using various surface conditioning and adhesive systems

Author of the article	year	Preparation of PEEK surface		
		Surface conditioning (prepare)	**Adhesive system**	**Shear bond strength (MPa)**
Schmidlin PR et al.	2017	Sulfuric acid 96% Sandblasting 50 µm	Heliobond Relyx™ Unicem Heliobond	18.2±5.4 19.0±3.4 13.5±2.4
Zhou L et al.	2014	Sulfuric acid 98 %	SE Bond/Clearfil AP-X™ Relyx™ Unicem	8.7±0.2 7.4±0.6
		Hydrofl uoric acid 9.5%	SE Bond/Clearfil AP-X™ Relyx™ Unicem	2.8±0.2 0
		Sandblasting 50 µm	Relyx™ Unicem SE Bond/Clearfil AP-X™	1.4±0.2 5.3±0.6
		Sandblasting 100 µm	Relyx™ Unicem	0

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 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)**.**

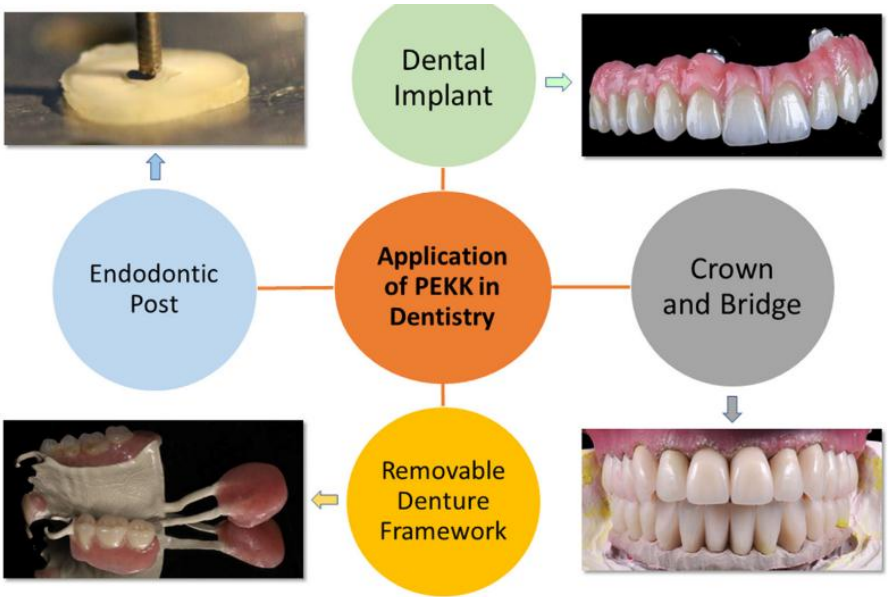

Figure 3: Major application of PEEK in Dentistry (Najeeb *et al*., 2016)

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 biocompatility, 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 claps 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 desing 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 compararable 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). Futhermore, 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 rehabitation of an edentulous patient. The authors reported high patient satisfaction with function and esthetics after 6 months (Spies *et al*., 2019).

1.7 PEEK as clasp material and it's 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. In Micovic *et al*. (2021) study, two PEEK materials were milled using CAD/CAM technology, while one material was pressed (Figure 4). 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).

Figure 4: RDP clasp specimens made of CoCrMo, PEEKmilled1, PEEKmilled2, and PEEKpressed

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).

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).

1.8 PEEK as replacement metal framework (Case report)

A 56-year-old female patient presented wearing a maxillary complete denture opposing a bilateral metallic RPD. Her chief complaints were a metallic taste sensation, compromised esthetics, and need for better mastication with stable prostheses. (Harb *et al*., 2019).

The treatment plan was to construct a new maxillary conventional denture and mandibular RPD with PEEK framework using CAD/CAM milling technology, the steps of fabrication are shown in figures (5-14)

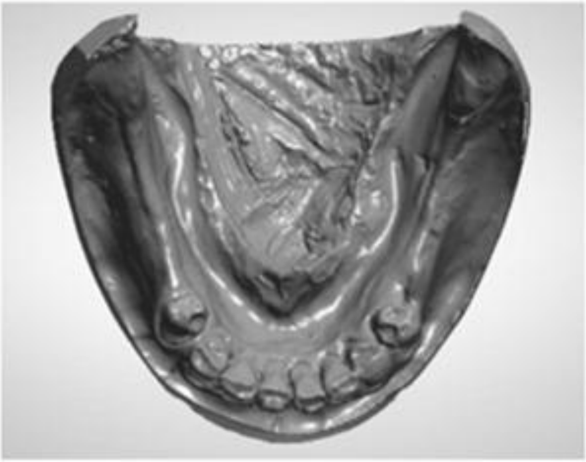

Figure 5:Virtual model after scanning of the definitive cast.

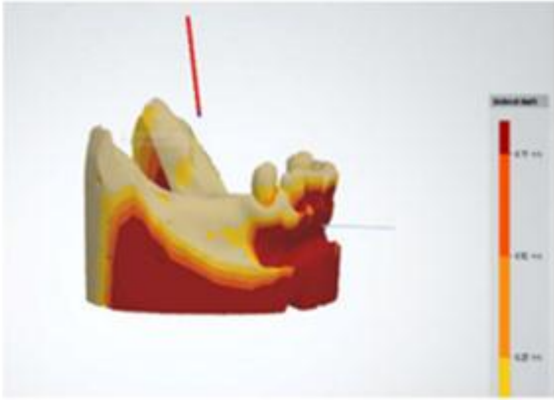

Figure6:Digital surveying.

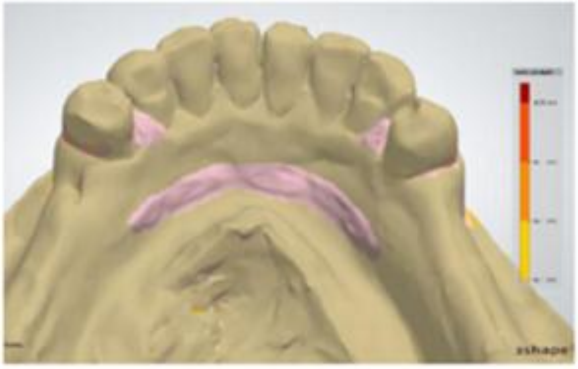

Figure7:Relief under lingual bar and minor connectors crossing gingival

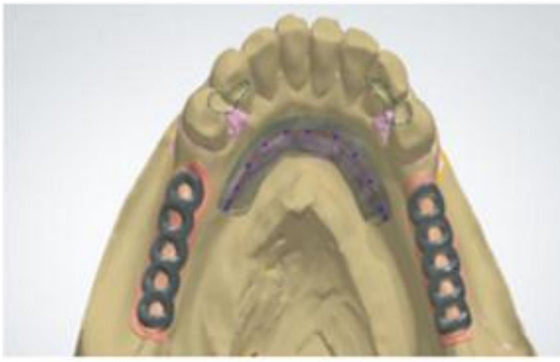

Figure8:Retention grids and major connector in place.

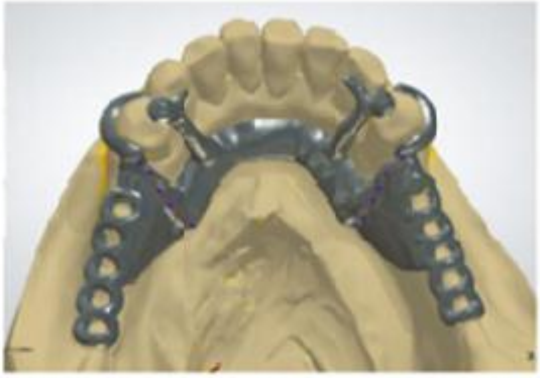

Figure9:Rests, minor connectors, and external finish lines inplace

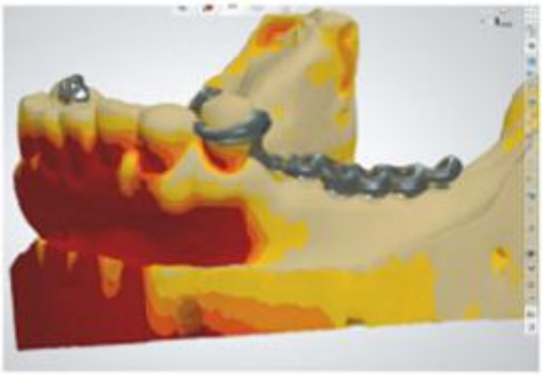

Figure10Relation of the clasp to the survey line

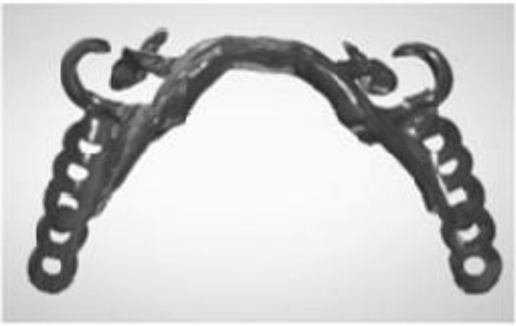

Figure 11:Fitting surface of the finished framework

Figure 12:Resin pattern of the framework made with prototyping technology

Figure 13: Trial of the PEEK framework.

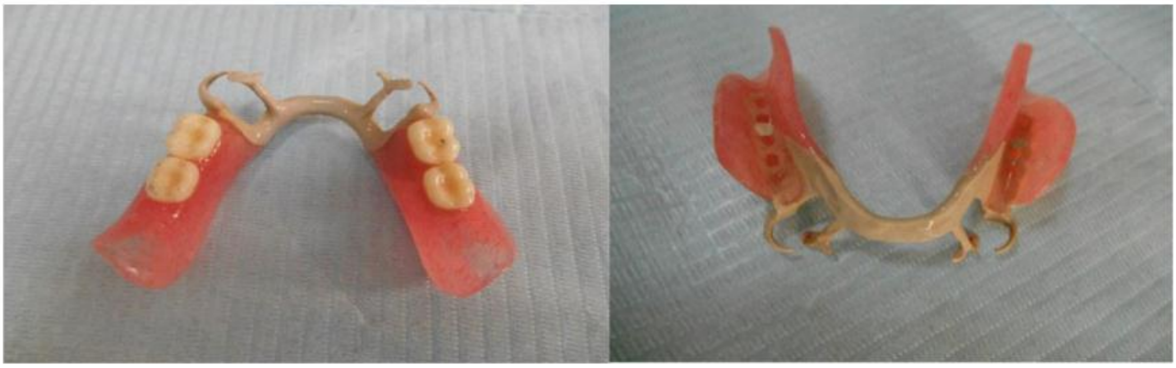

Figure 14: Finished prosthesis

After RPD insertion, the definitive RPD was physiologically relined with ZOE and replaced with acrylic resin. The RPD was delivered to the patient after occlusal adjustments (Fig. 13). The patient reported satisfaction with the prostheses and appreciated the general esthetics. The stability and retention achieved were fairly good, and the patient was satisfied with function.

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.

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