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Peek-prospective prosthesis material: A narrative review

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Abstract
Polyetheretherketone (PEEK) is a thermoplastic polymer that has many potential uses in dentistry. This review aims to summarize the reported applications of PEEK as a prosthetic material, the research conducted in regard to its properties concerning prosthetic applications and the future prospects of PEEK as a provisional or permanent prosthetic material. Original scientific articles published in Medline-Pubmed database were electronically searched. Articles published in English were identified, regardless of the year of publication, using a variety of keywords in combination. The studies relevant to our review were critically analysed and summarized. As a result it was found that due to the favorable mechanical and physical properties of PEEK, it can serve as an appropriate alternative material for various uses in dentistry. However, for further dental applications extensive research and clinical trials are required.

Keywords: PEEK, polyetheretherketone, dentistry, bioactivity, fixed prosthesis, removable prosthesis, implants

Introduction
Oral rehabilitation using CAD/CAM technology is recent trend that has gained popularity due its efficiency in various prosthesis fabrication. Amongst the various CAD/CAM Polymers available the most widely used are PMMA-, composite resin-, or polyetheretherketone (PEEK) - based materials. PEEK represents a relatively new material that got introduced to dentistry due its performance as a chemically inert biomaterial [1]. PEEK's chemical structure makes it exhibit stable chemical and physical properties such as resistance to radiation damage, resistance to attack by most of the substances (except sulfuric acid), wear resistance and stability at high temperatures (above 300 °C). PEEK has displayed neither toxic nor mutagenic effects in both *in vitro* and *in vivo* examination, therefore it is indicated in patients with titanium allergy [2-5].

In dentistry, PEEK is currently introduced for implants [6], provisional and healing abutments [7, 8], implant supported bars and dental clasps [9]. PEEK presents as an alternative infexible material for removable partial denture prosthesis frameworks. PEEK has been proposed for crowns and bridges but due to its grayish pigmentation and opacity, PEEK demands veneering. As a result of this, PEEK has not gained much attention in restorative and prosthetic dentistry [10].

This narrative aims to summarize the reported applications of PEEK as a prosthetic material, the research conducted in regard to its properties concerning prosthetic applications and the future prospects of PEEK as a provisional or permanent prosthetic material.

Materials and Methods
An electronic search of the literature was carried out using Medline-Pubmed database using keywords 'PEEK', 'polyetheretherketone', 'dentistry', 'dental', 'bioactivity', 'fixed prosthesis', 'removable prosthesis', 'implants' in combination. Articles about PEEK's properties, its prosthetic applications and the reported outcomes of PEEK were identified. *In vitro* and *in vivo* studies in human beings were included. Papers whose full text versions could not be retrieved were excluded. Papers in language other than English were excluded. Animal

studies were excluded. All relevant papers were critically analyzed and summarized.

Literature search and results

Initial literature search identified 154 articles out of which papers not in English and articles on animal studies related to PEEK were excluded. After a thorough screening, articles related to properties of PEEK and applications of PEEK in Prosthodontics and Implantology were included, resulting in 83 articles under focus. 66 articles were based on *in vitro* or *in vivo* studies of PEEK, 10 were clinical case reports and 7 were review articles.

Discussion

What is PEEK: PEEK is a synthetic, biocompatible, tooth colored polymeric material that was introduced in 1978 by a group of English scientists. During 1980's, its initial commercial application was seen in manufacture of aircrafts, turbine blades and automobile industries [2, 11]. By late 1990's, this polymer became a prospective alternate for metal components, especially in orthopedic, spinal and traumatic applications [3, 12]. Since April 1998, PEEK has presented as an excellent biocompatible implant material (Invibio Ltd., Thornton-Cleveleys, United Kingdom) [13].

PEEK is a semi crystalline linear polycyclic aromatic polymer belonging to polyaryletherketone family and consists of an aromatic molecular chain backbone, interconnected by ketone and ether functional groups between the aryl rings ($(-C_6H_4-OC_6H_4-O-C_6H_4-CO-)_n$) [2]. A polymerization reaction of etheretherketone via step-growth dialkylation reaction of bis-phenolates is involved in production of polyetheretherketone [14]. This chemical structure makes PEEK exhibit stable chemical and physical properties (Table 1). Lieberman *et al*., in its *in vitro* study found that PEEK exhibits the lowest solubility and water absorption values compared to polymethyl-methacrylate (PMMA) and composite [21]. PEEK is radiolucent and opalescent grey in colour. Other *in vitro* and *in vivo* studies demonstrated PEEK as a biologically inert and biocompatible material with neither toxic nor mutagenic effects. PEEK is indicated in patients with titanium allergy owing to its least allergic potential [22, 23]. However, a rare case of tissue reaction to PEEK is reported by Maldonado- Naranjo *et al*. Allergic symptoms reported were angioedema, itching, swelling of tongues and skin thickening following an intervertebral PEEK cage intervention [11].

Table 1: Properties of PEEK

Thermal Stability	Upto 335.8 °C [15]
Flexural Modulus	140-170 MPa [16]
Density	1300 kg/m [3, 5]
Thermal conductivity	0.29 W/mK [17]
Young's elastic modulus	3-4 GPa [17, 18]
Elastic modulus of CFR PEEK	18 GPa [19]
Elastic modulus of GFR PEEK	12 GPa [20]
Tensile Strength	80 MPa [19]

PEEK exhibits low Young's (elastic) modulus (3-4 GPa) which is close to that of human cortical bone (10-32 GPa). When other materials like carbon fibers are incorporated, the elastic modulus increases up to 18 GPa allowing PEEK to demonstrate a homogenous stress distribution [17-20]. This factor along with a tensile stress analogous to bone, makes PEEK an appropriate implant material.

PEEK as an Implant material

Titanium implants is being widely used at present but it displays certain disadvantages such as hypersensitivity, opacity posing esthetic problems and most importantly excessive stresses at the implant-bone interface due to the gradient contrast in the elastic moduli of implant and surrounding bone [18]. As an alternative to Titanium implants, PEEK was proposed to be a viable implant biomaterial due to its resistance to degradation *in vivo* and elastic modulus similar to that of cortical bone. It was first commercialized in April 1998 as a bioinert material for implants (Invibio Ltd., Thornton-Cleveleys, UK) [3].

Finite-element analysis (FEA) studies of carbon-fiber reinforced PEEK (CFR-PEEK) implants have displayed that less stress shielding is induced compared to titanium [20, 6]. However, a recent FEA study concluded that, compared to titanium, CFR-PEEK implants do not present any significant advantage considering the stress distribution to the peri-implant bone [12]. Also, the interfacial adhesion between carbon fibers (CFs) and PEEK matrix is poor due to the non-polar nature and low wettability CFs which negatively impact the mechanical properties of CF/PEEK composites. A study instituted a technique to improve the interface between CFs and PEEK by chemical grafting aminated polyetheretherketone (PEEK-NH_2) on CFs to create an interfacial layer which has competency with the PEEK matrix [24].

Bone-implant contact (BIC) values were found to be significantly higher in titanium coated implants when compared to uncoated CFR-PEEK implants [25]. A study evaluated adjacent mandibular implants made of titanium, zirconia and pure PEEK and results suggest that PEEK presented lowest BIC at 4 months [26]. Khonsari *et al*. has published three cases of severe infections resulting from PEEK-based compounds [27]. An improved osteogenic differentiation and higher implant fixation *in vivo* is observed with porous PEEK implant surface compared to smooth PEEK and Ti-coated PEEK [28]. This is due to the high porosity of porous PEEK which allows bone ingrowth thereby increasing mechanical interlocking of porous PEEK [29].

PEEK implants display bio-inertness and have hydrophobic surfaces which are not suitable for fast bone cell adhesion. A coating of Hydroxyapatite (HA) presented promising results compared with uncoated PEEK [3, 30]. TiO_2-coated PEEK is a more promising choice of implant biomaterial followed by TiO_2-blended PEEK [31, 32]. Incorporation of nano-sized hydroxyfluorapatite (n-FHA) particles impart anti-microbial properties thereby reducing chances of peri-implantitis [33]. A biocomposite of HA/PEEK created by a compounding and injection-molding technique has demonstrated to exhibit enhanced osteogenesis [34].

The response of osteoprogenitor cells to Titanium plasma-sprayed PEEK (Ti-PEEK) was assessed, and the results were remarkable. Within 24 hours, the accumulation of calcium on Ti-PEEK surfaces exceeded that on Titanium (Ti) and PEEK surfaces by 305% and 470%, respectively. Therefore, there is substantial evidence to suggest that Ti-PEEK surfaces could promote contact osteogenesis through the rapid formation of cement lines originating from undifferentiated osteoprogenitor cells [35].

Xu *et al*. aimed to develop a novel CFR-PEEK-nanohydroxyapatite (PEEK/CF/n-HA) with a micro/nano-topographical surface to enhance osteogenesis, positioning it as a potential bioactive material for bone grafting and bone tissue engineering applications [36]. In a related study, Han *et* *al*. demonstrated that FDM-printed (Fused Deposition Modeling) CFR-PEEK possesses superior mechanical properties compared to traditionally printed PEEK. Furthermore, the FDM process results in a highly roughened surface, which is beneficial for cell attachment. Consequently, CFR-PEEK shows significant potential for use in orthopedic or dental implant materials, particularly in the areas of bone repair, regeneration, and tissue engineering applications [37].

The hydrophilicity and surface roughness of PEEK can be enchanced through series of rapid, ambient-temperature sulfonation procedures [38]. A recent investigation improved the bioactivity of PEEK by creating a 3D porous substrate through sulfonation. This substrate was then integrated with strontium (Sr) and coated with an adiponectin (APN) protein layer using a polydopamine-assisted method. Nanostructures emerged on the PEEK-Sr-APN surfaces, and the APN coatings could regulate the Sr release rate, further influencing cell-material interactions. *In vitro* tests showed a significant increase in cell proliferation and differentiation when regulated by Sr/APN. This research highlights the potential of bioactive Sr and APN as effective agents for bio-functional bone regeneration or replacement and enhances the osteointegration of PEEK implants in clinical applications [39].

The Laser-assisted biomimetic (LAB) process, a recent innovation, has been developed to enhance the cytocompatibility of PEEK surfaces with osteoblastic cells, making it a valuable new method for creating osteoconductive PEEK-based implants [40].

Parmigiani-Izquierdo *et al*. reported a case involving Zirconia implants with PEEK restorations and composite coatings for replacing upper molars. PEEK was noted for its role in absorbing occlusal loads during chewing [41]. Berrone *et al*. undertook a correction of mandibular asymmetry following fibula reconstruction, employing a custom-made PEEK onlay [42]. Furthermore, the study by Bayer *et al*. highlights that PEEK meets the necessary criteria for retentive clips used on round bars [43].

In their current form, both PEEK and CFR-PEEK implants are not fully capable of withstanding the insertion force required for primary stability essential for immediate loading. However, the torque resilience that these two variants of PEEK can achieve might be adequate for a two-stage implantation process. To enhance the torque resistance of PEEK implant materials, it's essential to develop a new manufacturing method. This method should strengthen the PEEK base with continuous multi-directional carbon fibers, in contrast to the axially parallel fibers used in the current PEEK compound [44].

PEEK as an abutment material

Recent advancements have seen the introduction of PEEK abutments for the fabrication of implant-supported provisional crowns [45-47]. In comparison to titanium abutments, PEEK provisional abutments exhibit lower fracture resistance. Consequently, they are advised for short-term use, typically for provisional fixed prostheses lasting 1-3 months, as opposed to titanium temporary abutments which are suitable for longer durations of 6-12 months [16, 48-49]. Additionally, a study has indicated that electronic percussive testing may not be a reliable method for assessing implant stability when using polyetheretherketone (PEEK) healing abutments [50].

Using a PEEK-made abutment screw could offer benefits over traditional metal screws due to its lower fracture resistance, comparable elasticity, enhanced torque efficiency, and ease of removal if a fracture occurs [51, 52]. When considering masticatory forces, PEEK implant crowns appear suitable for definitive implant-supported restorations. This suitability is evident as there were no instances of implant screw loosening or damage to the veneer or PEEK framework during masticatory simulation. Additionally, the bacterial tightness at the implant-abutment interface of screw-retained one-piece PEEK implant crowns is more advantageous when compared to superstructures made from conventional materials [53].

Abutments made from ceramic-reinforced PEEK with a titanium base could serve as an alternative to zirconia abutments that also have a titanium base. However, it's important to note that the fracture strengths of both these groups - ceramic-reinforced PEEK and zirconia – are significantly lower when compared to abutments made entirely of titanium [54].

Koutouzis *et al*. noted minimal marginal bone loss with both titanium and PEEK healing abutments [8]. In addition, PEEK abutments are cost-effective, can be readily modified to support a temporary prosthesis at the time of implant placement, and their color contributes to achieving satisfactory provisional aesthetic results [49, 7]. Tetelman *et al*. demonstrated through three clinical cases that using PEEK as a provisional abutment is effective, providing acceptable labial/buccal contours and support for the papillary tissues [7].

Al-Rabab'ah *et al*. reported 3 successful clinical instances where PEEK was used for different purposes; as a custom-made abutment, a framework material for full mouth rehabilitation and as a superstructure on tilted implants.[55]

PEEK as a fixed dental prostheses material

PEEK blanks typically exhibit a grayish-brown or pearl-white opaque hue, making them less suitable for monolithic aesthetic dental restorations, particularly in the anterior region. Consequently, veneering becomes necessary. However, adhering veneering composite resin materials to PEEK presents a challenge due to its complex chemical structure [56].

Laboratory research has indicated that milled PEEK crowns with a 0° taper exhibit the lowest retention force values, while those with a 2° taper have the highest. However, for pressed PEEK crowns, the taper angle does not significantly influence retention force [57-59]. In a separate study, Stock *et al*. concluded that PEEK is an appropriate material for primary crowns, irrespective of the taper and the material used for the secondary crown [60]. Additionally, Schubert found that PEEK secondary crowns maintain stable retentive force values over a simulated 10-year aging period, showing no signs of deterioration. In contrast, the retentive force values of electroformed secondary crowns tend to increase over time [61].

Additionally, Stawarczyk *et al*. conducted a study to assess the impact of various fabrication methods on the fracture load. They concluded that PEEK/C, when reinforced with other inorganic fillers, has potential for use as a material in the making of crowns and bridges [62].

Nazari *et al*., in their *in vitro* study, concluded that implant-supported three-unit fixed partial dentures (FPDs) made from zirconia, metal-ceramic, and PEEK materials are capable of withstanding occlusal forces, even in situations of excessive crown height space [63].

Further research has explored various pre-treatment methods applied to PEEK surfaces, such as abrasion, acid etching, laser treatment, or plasma techniques. These studies found that a hydrophobic adhesive could successfully bond to both PEEK and a composite resin. However, universal composite

resin cement did not seem to bond effectively to PEEK [64, 65].
For effective bonding between PEEK and composite materials, it's recommended to clean and roughen the surface. Surface conditioning prior to bonding is crucial for achieving good adhesion [66, 67]. Several studies have investigated the effects of surface modification of PEEK for bonding with various luting agents. Techniques like air abrasion and a combination of air abrasion with piranha solution, along with adhesives such as Viso. Link, Signum PEEK Bond, and Monobond Plus / Heliobond, have been shown to create reliable bond strengths for veneering PEEK with resin composites [68-72]. Among these adhesive systems, Visio.link has demonstrated statistically higher shear bond strength values compared to Signum PEEK Bond [73].
Also, sulfuric acid etching have demonstrated improved bond strengths with optimal concentration of sulfuric acid at 90% and 98% [74].
The findings from the aforementioned studies indicate that PEEK is a viable option as a coping material under resin-composite. Given that the mechanical properties of PEEK closely resemble those of dentin and enamel, PEEK may offer advantages over traditional alloy and ceramic restorations.

PEEK CAD-CAM milled Fixed Partial Denture

CAD-CAM designed composites and polymethylmethacrylate (PMMA) fixed dentures are known to have better mechanical properties compared to conventional fixed dentures. PEEK stands out for its higher fracture resistance, making it a strong alternative for CAD-CAM restorations. In terms of abrasive resistance, PEEK is on par with metallic alloys. However, it's noteworthy that there haven't been any clinical studies comparing the abrasion caused by PEEK crowns on teeth. Taking into account its mechanical properties, PEEK fixed partial dentures are anticipated to exhibit a satisfactory survival rate [16].

PEEK as a Removable Prostheses Material

PEEK CAD/CAM systems are suitable for fabricating dentures.[75] In their research, Tannous *et al*. found that denture clasps made from PEEK exhibit lower retentive forces compared to those made from cobalt-chromium (Co-Cr) [9]. Nonetheless, there is evidence in the literature of a successful 2-year case report advocating for the use of non-filler PEEK as a clasp retainer in mandibular Kennedy's class I situations [76].
Zoidis *et al*. introduced an innovative design for removable dental prostheses, utilizing a modified PEEK material that includes 20% ceramic fillers (BioHPP) in conjunction with acrylic resin [5]. In a clinical case, Hahnel *et al*. reported on a patient with significantly reduced occlusal vertical dimension. The placement of a double crown-retained prosthesis with a PEEK framework effectively restored both function and aesthetics for the patient [77]. Additionally, the use of PEEK overdenture frameworks, especially in combination with high noble retentive parts, presents a promising alternative to titanium for patients with allergies to base metals. This was demonstrated in a clinical case by Zoidis, where a PEEK overlay denture framework was employed over high noble ball attachments, enhancing the strength of a mandibular prosthesis for a patient allergic to base metals [78].
A recent advancement in the field of PEEK involves the creation of hybrid PEEK-acrylic resin prostheses. These are being used in various dental restorative applications, including full arch implant-supported removable prostheses (with the female part of bars milled from PEEK), full arch implant-supported fixed prostheses, and the all-on-four concept [79-81].
In a Finite Element Analysis (FEA) study, the biomechanical behavior of an implant system utilizing the All-on-Four technique with nickel-chromium and PEEK bars was examined. This study revealed that PEEK bars exhibited the highest peak stresses [81].
Despite the limitations of clinical studies, it has been proposed that hybrid PEEK-acrylic resin prostheses supported by implants for full arch rehabilitation could be a feasible treatment option. However, this assertion still necessitates further validation over a longer term.

PEEK in Maxillofacial Prosthesis

PEEK OPTIMA, a reinforced form of poly-ether-etherketone, is recognized for its biocompatibility, similarity to the flexural modulus of bone, resistance to cracking, easy polishing, and machinability. These properties make it a suitable material for the palatal section of maxillary obturator prostheses, especially for patients with extensive oral-nasal defects [82, 83]. However, the effectiveness of PEEK obturators still requires more comprehensive evaluation, particularly in comparison with traditional acrylic prostheses.

Conclusion

PEEK, known for its mechanical robustness, biocompatibility, aesthetic color, and an elastic modulus akin to cortical bone, holds significant promise in various dental applications. However, its usage faces limitations due to a relatively lower fracture resistance and suboptimal stress distribution around implant-abutment interfaces, along with a modest Bone-to-Implant Contact (BIC), which restricts its role as a permanent abutment or implant material. Enhancing PEEK's bioactivity while preserving its mechanical integrity remains a critical challenge. This can be potentially addressed by incorporating materials like carbon fibers, glass fibers, or hydroxyapatite. Additionally, PEEK's advanced mechanical properties make it a compelling choice for fabricating CAD-CAM fixed and removable prostheses, offering advantages over traditional materials like acrylic. Nonetheless, further exploration through research and clinical trials is essential to fully unlock PEEK's potential and investigate modifications for broader dental applications.

Ethical statement

The study was based on literature review and therefore does not require ethical approval

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Conflict of interest

The authors of this article have no conflict of interest to declare.

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