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Surface Modification of Polyether Ether Ketone (PEEK) in Osseointegration of Dental Implant

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Abstract

Background: The "Polyetheretherketone (PEEK)" is a linear, polycyclic, semi-crystalline thermoplastic which has emerged as an alternative to metals and is widely used in biomaterials. It is also used in dental implants as an abutment, implant structure, or a superstructure.

Purpose: This study is aimed to review the relevant studies on various ways to modify PEEK to deal with its limited bioactivity and make it ideal material for dental implants.

Methodology: An online literature search was performed on Google Scholar using various search terms like "dental implants," "PEEK," "osseointegration," "modification," and "surface treatment."

Findings: Several viable approaches have been suggested to improve PEEK's bioactivity. A lot of approaches are based on improving the roughness of surface, while improving the osseo-conductive coating materials and hydrophilicity.

Conclusion: There are different approaches to modify PEEK to remove its limitations related to bioactivity. It is possible to use melt-blending with "bioactive nanoparticles" to develop "bioactive nanocomposites," while using "gas plasma etching, spin-coating, deploying plasma-ion, and electron beam" to modify PEEK implants to be more bioactive. However, further experiments will be required to certify these materials for using in dental implants.

Keyword: Dental Implants, PEEK, Osseo-conductive Coating, Osseointegration, Biomaterials, Polyetheretherketone

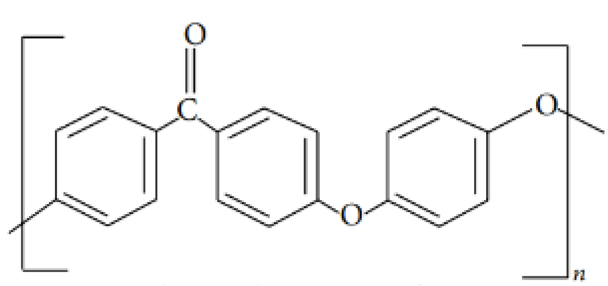
Introduction: Dental implant is an artificial fixture planted surgically within the alveolar bone functioning as a root to support and stabilize a detachable/fixed prosthesis[1,2]. There are two responses from the tissue taking place after implanting a biomaterial. Failure of implant is observed due to formation of a fibrous tissue between the bone and implant. Implant is supposed to be "osseo-integrated or osteo-integrated" in the alveolar bone with the formation of intimate and direct contact of bone implant [3]. There are different factors responsible for "osseo-integration" phenomenon. Surgical procedure, material used in implant, and healing duration are some of the factors responsible for successful dental implants[3,4].

Usually, titanium, zirconia and its alloys are used in implants[5,6]. This way, "fiber reinforced composite (FRC)" has a great potential in future but it must be bio-compatible and have ideal properties to induce the formation of bone across the implant[7,8]. High hydrophilicity, ideal design, and rough surface are some of the desirable properties of implant material [9-11]. The osseointegration level can be improved in implants by coating the same with calcium phosphate and other osteoconductive coatings[11, 12].

Over the past decades, endosseous implants have been made widely with commercial Grade 2 or Grade 4 titanium [13]. However, titanium has a lot of problems. Due to high elasticity of alloys, titanium implants can damage periodontal bone and lead to stress-shielding[14,15]. In addition, some of the rare cases have been observed in studies related to hypersensitivity among patients to titanium implants[16,17]. Titanium implants can also cause leakage of ions and wear debris [18]. When dental implant can be seen from a thin "biotype gingiva" as titanium is known to be a dark material, aesthetics can be affected.

Background: As a "semicrystalline thermoplastic," PEEK or "Polyetheretherketone" is synthesized via polymerization of growth with "dialkylation of biophenolate salts." PEEK is a polymeric, organic, and synthetic material which looks like tooth to serve as an aesthetic material for dental implants[19.] Figure 1 illustrates the overall chemical structure of PEEK. It holds great biomechanical properties and chemical resistance. Young's PEEK modulus is up to 3.6 GPa pure and its "carbon-reinforced PEEK (CFR-PEEK)" is up to 18 GPa, which is nearby cortical bone [7,20,21]. So, it is shown that PEEK is capable to have reduced "stress-shielding" in comparison to titanium [22]. However, PEEK can stimulate reduced differentiation of osteoblast[23]. Speaking of which, PEEK is used as a bioinert material without any inherent "osseo-conductive properties"[24].

Figure 1 – PEEK's chemical structure[37]



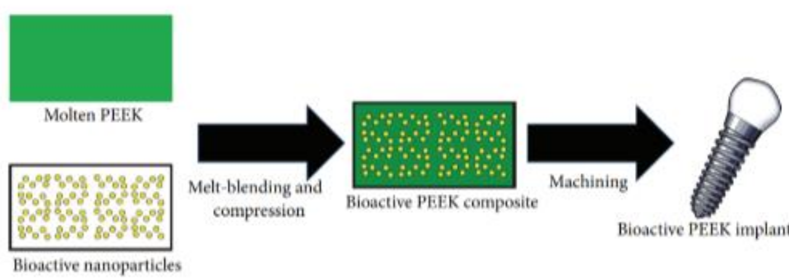
Chemical structure of PEEK

PEEK can be blended and coated using bioactive paticles to improve roughness of surface and osseo-conductive properties. However, plasma-spraying contains high temperatures to affect PEEK. In addition, dense coverings of calcium phosphate can delaminate on PEEK due to bond strength lower than coated implants made of titanium(Ti)[25,26]. In addition, combination of particles and PEEK in micrometer size makes mechanical strength lower than CFR-PEEK or PEEK in its purest form [27]. Hence, a lot of research has been done for modifying PEEK by blending or coating the same with nanosized particles and production of nano-level surface topography. This review paper discusses recent studies on production of nano-level and bioactive nanocomposites to determine the feasibility of PEEK as dental implant.

It is possible to add bioactive particles in PEEK for creating bioactive implants[27]. Hydroxyapatite is a chemical bioceramic which appears like bone and it induces the formation of bone along dental implants [11]. The micrometer sized "Hydroxyapatite particles (HAp)" have been blended and melted with PEEK-HAp composites to be produced with PEEK but these could be harder to be used as implants due to inferior mechanical properties because of improper bonding among hydroxyapatite and PEEK particles [27,28].

Bioactive PEEK composite implants can be produced for getting melt-blending nanoparticles and improving mechanical properties at the same time [29]. Figure 2 shows schematic illustration of melt-blending of PEEK, which is proposed by Wan et al. [29] and Wu et al.[30] with bioactive nanofillers.

Figure 2 – Schematic illustration of melt-blending process for producing "bioactive PEEK composites" [29,30,37]



First of all, the nanofillers and PEEK powder are co-dispersed for formation of proper suspension in an ideal solvent, which is then removed with the drying process in oven and powdered blend is added in the implant-shaped mould. The preheating of mould and powdered blends is done to around 150^oC at the pressure of 35 MPa. After reaching PEEK melting point, the particles of bioactive filler are solid while the polymer is melted. After keeping the high temperature for ten minutes, air-cooling of composite implants is done at 150^oC. After cooling, the solid PEEK matrix is composed with nanofillers (Figure 2).

PEEK composites can be produced with improved bioactivity and mechanical properties by using nanosized particles as listed in Table 1. Using titanium dioxide (TiO_2) nanosized particles can improve osseo-integration to PEEK[30]. With computerized 3D tomography, it is observed that higher bone amount forms "PEEK/nano-TiO_2 cylindrical implants" and mechanical properties have been improved as compared to pure PEEK due to higher nanofiller particles[30]. Studies have widely explored the impact of "free TiO_2 particles" on cellular activity. It is also observed that carcinogenic/inflammatory response can be triggered in cells and nerve tissue can be damaged [31,32]. Meanwhile, some studies have found that the cellular differentiation and proliferation can be increased by TiO_2 with solid cores or coatings [33-35]. However, potential release of those particles from nano-TiO_2 or PEEK composites has not been studied till date after mechanical load.

Table 1 – List of "Bioactive PEEK Nano-composites" and their biomechanical characteristics

Component	Size of Particle	Modulus (in GPa)	Tensile Strength (in MPa)	Contact angle (in degrees)	Studies on animal samples	Reference
PEEK-nHAF	85±10 nm long and 22±4 nm wide	12.1±0.4	137.6±9.1	71.5	Yes	29
PEEK-nTiO_2	NA	3.8	93	NA	Yes	30
CFR-PEEK-nHAp	<200nm	NA	NA	10(with plasma) and 75(without plasma treatment)	No	36

Discussion: When it comes to produce "PEEK nanocomposites," surface modification changes PEEK surface with minimal or no impact. There are four processes used till date to make small changes on the PEEK implant surface – "gas plasma etching, spin-coating, electron beam deposition, and plasma-ion immersion implantation (PIII)" [38-40].

There are various surface changes aimed for making PEEK more bioactive (Table 2).

Table 2 – Surface Alterations for PEEK

Surface alterations	Pore size/surface roughness	Angle of contact (in degrees)	Studies on animal samples	References
Gas Plasma etching				
Oxygen/argon(O_2/Ar)	RMS = 9 to 19 nanometer	5-40	No	41
Ammonia(NH_3)	RMS = 3 to 7 nanometer	45-90	No	42
O_2	$R_a = 75.33 \pm 10.66$ nm	52	Yes	43
Spin Coating				
nHAp	$S_a = 0.686 \pm 0.14\ \mu m$ to $0.93 \pm 0.25\ \mu m$	53 ± 4.4	Yes	38
Electronic beam TiO_2				
Anodized	Pore size – 70 nm	≈0	Yes	44
Traditional	NA	54	No	44
Plasma-Ion Immersion Implantation (PIII)				
Diamond-looking carbon	RMS = 5.42 nanometer	≈55	No	45
TiO_2	Pore size – 150 to 200 nm	NA	No	46

Spin-Coating using "Nanohydroxyapatite": Considering the issues of dense "hydroxyapatite coating", a lot of studies have suggested thinner coatings for coat implants [47]. Spin coating consists of deposition of thin nano-HA layer, precipitated in organic solvents, surfactants, and aqueous solution of "Phosphoric acid(H_3PO_4) and calcium nitrate [$Ca(NO_3)_2$]" on the implants. Implants are spun during the deposition at high speeds and heat-treated for formation of coating [38].

Barkarmo et al. [38]evaluated "spin-coated PEEK implants" and found that mean torque of implanted, spin-covered discs was not higher than the same of uncoated implants and various implants were failed during the study. However, higher torques were found in other studies by Johansson et al. [48] and Barkarmo et al. [49] in comparison to uncoated PEEK when a cylindrical, threaded design was added to modify the implant design. Proper implant design is vital and it is also an ideal bioactive coating for proper dental implants coated with PEEK.

Gas Plasma Nanoetching: PEEK implants are exposed to weak plasma gases like water vapor, ammonia, and argon/oxygen to achieve nano-etching [41,42,46]. PEEK plasma treatment has a lot of functional groups on the surface to make a hydrophilic surface for plasma treatment[50]. The ability for producing nano-level sturdiness on the surface and very low angle of water contact is the main aspect of plasma treatment on PEEK surface[41].

Electron Beam Deposition: The process of electron beam deposition can deposit and decompose non-volatile fragments on substrate[39]. The process of "e-beam deposition" can deposit and decompose non-volatile fragments on substratum[39]. A thin coating of titanium on PEEK has been found to improve cellular adhesion and wettability[44]. With the anodization of PEEK titanium coating produced by deposition of e-beam, it is transformed into a 2 μm thick, highly nano-porous, and crack-free layer of $nTiO_2$ or Titanium oxide that can carry bone-morphogenetic protein 2(BMP2)[43].

Plasma immersion ion implantation (PIII): It is possible to coat a substrate with a thin film of various particles to place the substate in particle plasma pulsed constantly with high amount of negative charges leading to plasma ions to be increased and implanted on the substrate surface[40]. This process is called PIII. The nano titanium dioxide particles coat the PEEK with

PIII[51]. Lu et al[51] found that those implants can have partial antimicrobial activity over "Escherichia coli and Staphylococcus aureus".

Related Studies: A lot of studies have made efforts to develop alternatives for titanium implants like zirconia with high elastic modules and low degradation of temperature[52,53]. Polyetheretherketone (PEEK) and other polymeric compounds have been created as added substitutes. In 1978, PEEK was developed as a "semi-crystalline linear polycyclic thermoplastic"[54]. It is applied as implant body, implant abutment, and superstructure. PEEK is a leading member of "PAEK (poly-aryl-ether-ketone) polymer family" with high-temperature stability that can exceed up to 300^{o}C and has high chemical and mechanical strength. It is a key alternative to metal compounds in orthopedics [55].

PEEK consists of aromatic backbone with combinations of "ether (-O-) and ketone (-CO-) functional groups" among aryl rings. It has low density (1.32 g/cm^3), high stability, low elastic modulus (3-4 GPa), and insolubility [56,57]. PEEK has some form of clinical benefit as a material for dental implant in comparison to titanium. First of all, it doesn't cause much allergic and hypersensitive reactions. Some studies have observed that Titanium is allergen [58]. Secondly, it doesn't cause much artifacts on "magnetic resonance imaging" and is radiolucent [45]. Third, there is no metallic color. It is in beige color with a hint of gray and it looks more natural than titanium. Fourth, it is a versatile material and it can be personalized for specific purposes by altering its surface or bulk properties.

PEEK is used as implant material in the abutment, implant body, and superstructure. There are limited applications in implant body for bench tests and there is a lack of report on applying the same to the mandible as implant structure. When using PEEK as the body for dental implant, it may have less "stress shielding" as compared to titanium because it is closely compatible to bone and PEEK mechanical properties [59]. Even though PEEK is applicable as a provisional or healing abutment, there is a lack of information on final abutment.

Becker[60] showed an approach to achieve the emergence in dental implant areas using a PEEK abutment. Koutouzis [61] evaluated the responses of hard and soft tissue to Ti and provisional abutments of PEEK and found no significant difference among Ti and PEEK in hard- and soft-tissue responses after provisional abutment. Another study found that PEEK abutments reinforced by titanium can be an effective substitute in comparison to traditional Ti abutments as PEEK can preserve soft tissue and bone height[62]. There is a lack of information on long-term PEEK assessment. There is a lack of study on controlled clinical assessment and PEEK superstructure [63].

A lot of reinforced PEEK composites are developed like "glass fiber-reinforced PEEK (GFR-PEEK)" and "carbon fiber-reinforced PEEK (CFR-PEEK)" but CFR-PEEK has higher elastic modulus at 18 GPa, as compared to GFR-PEEK at 12 GPa[59,64]. PEEK elastic modulus can be customized as per the titanium alloy or cortical bone with CFR composites at different orientations and fiber lengths. CFR-PEEK has been widely studied in medical implant community because of its superior mechanical properties, versatility, compatibility with cutting-edge scanning techniques, and biocompatibility[65,66]. There are different shapes of this material with several mechanical, physical, and surface properties [67]. Table 3 lists elastic modulus (GPa) of various materials.

Table 3 – Elastic Modulus (GPa) of Materials

Materials	Elastic Modulus (GPa)	References
Cobalt-Chromium	180-210	68
Titanium	110	59
Porcelain	68.9	69
Zirconia	210	59
PEEK	3-4	64
PMMA(polymethyl methacrylate)	3-5	Suggestions
CFR-PEEK	18	64
Constant CFR-PEEK	150	65
GFR-PEEK	12	59
Enamel	40-83	71
Cortical Bone	14	72

Suggestions: There are different ways to modify PEEK at nanometer level to deal with its least bioactivity. It is possible to combine nanoparticles like HAF, TiO_2, and HAp with PEEK with melt-blending to generate bioactive nanocomposites. In addition, there are excellent tensile properties of these composites in comparison to pure PEEK. Despite having lower osteo-conductivity in PEEK as compared to titanium, "hydroxyfluoroapatite" can improve biocompatibility to gain osseointegration. In addition, there is significantly higher tensile properties of modified PEEK as compared to pure PEEK[37]. It is possible to coat PEEK with other bioactive materials using spin-coating, plasma spraying, electron-beam deposition, plasma gas etching, and implantation of plasma immersion ion [40-41,48,66].

Rust-Dawicki & Cook [67] compared PEEK dental implants coated and uncoated with titanium and their in vivo mechanical strength. The titanium-coated implant was 2000 Å thick due to deposition of plasma vapor to the implant surface. They performed in vivo test on canine femurs. The shear strength of uncoated implant was significantly higher after 4 weeks, but without any significant difference between uncoated and coated implants after 8 weeks. There was also lack of major difference in new bone growth or bone contact among two groups between 4 to 8 weeks. Bone contact was significantly higher in coated samples at 4 and 8 weeks. Since titanium is potentially hypersensitive in some areas, titanium coating might affect inflammatory and hypersensitive reactions [19]. There was no extreme inflammatory response in any samples and there was no inter-positionary fibrous tissue among the samples[67].

Unmodified PEEK has 80 to 90 degrees of water-contact angle (CA) as a bioinert material, which is closely related to a hydrophobic value[73]. Modified PEEK increases proliferation of cells due to increased hydrophilicity as wettability of implant surface and biomaterial affects the interaction between material and its nearby environment [74]. The UV irradiation can enhance the wettability of implant surface. The UV irradiation can enhance the wettability of surface. Qahtani et al. [73] made comparison between the wettability changes of four original implants like PEEK after UV-C and UV-A irradiation and found that implants hydrophilized a bit at 79 degrees of CA during UV-C irradiation. Xu et al. [75] used “micro-/nano-topographical structures” to develop “CFR-PEEK-nanohydroxyapatite” with some changes in oxygen plasma and sandblasting of surface. It was aimed to improve the osteogenesis as a bioactive material for applications like “bone tissue engineering and bone grafting” with improved osseointegration and biocompatibility.

There are different ways to modify PEEK at nanometer level to deal with its lack of bioactivity. PEEK can be combined with nanoparticles like HAp, HAF, and TiO2 through melt-blending for producing bioactive nanocomposites. In addition, these composites have very high tensile strength in comparison to pure form of PEEK. In addition, HAF is antibacterial to avoid early failures and peri-implantitis. Gas plasma etching, spin-coating, plasma-ion immersion, and electron beam decomposition can coat or modify the PEEK implant surface at nanometer level.

TiO2 and HAp nanocoatings produced by PIII and spin-coating can have bioactive surface properties. In addition, immobilized BMP-2 can be carried by PEEK due to anodized TiO_2 nanolayer coated by anodized beam of electrons that can further boost cellular function. However, a lot of studies have been confined to in vitro experiments. There is a lack of human and animal testing with PEEK implants. So, it has the risk of failure. Hence, a lot of in vivo experiments are needed to use nanomodified PEEK implants widely in clinical treatments.

Conclusion: Titanium and Ti alloys have been widely used in clinical settings since 1960s. These materials have solid physicochemical properties, biocompatibility, mechanical characteristics, and high resistance to corrosion and fatigue stress. However, elastic modulus of Ti is very high (110 GPa) as compared to cortical bone, i.e., 14 GPa. This difference may have risk of bone resorption, stress-shielding, and implant fracture. Additionally, titanium has been responsible for clinical symptoms like occasional allergies and hypersensitivity to metal, and contamination and degradation of surface due to scattered radiation and peri-implantitis. Titanium also doesn’t look natural and looks more metallic. So, there is a need for highly aesthetic implant.

A lot of studies have been conducted for development of alternatives of titanium implants like zirconia due to low degradation of temperature and high elastic modulus. However, other alternative developed is “polyetheretherketone (PEEK)” which is a polymeric compound developed in the year 1978. It is applicable as implant body, implant abutment, and superstructure. This review paper has discussed the applications of this composite material as dental implant and recent developments in this domain. Despite having a lot of benchmark tests and reports on surface modifications and reinforcement of PEEK, there is a lack of clinical tests where PEEK is used as dental implant. There is a need to have more clinical trials for implant bodies and abutment.

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