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Developments of PEEK (Polyetheretherketone) as a biomedical material: A focused review

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A B S T R A C T

The present review study highlights the progress of PEEK and its composite materials in biomedical applications. Various domain areas such as dentistry, knee implants, spine implants, crainoplasticity, hip replacement, anterior plate fixation etc. have been discussed. Many successful applications of PEEK have been explored from curing the lung tumour by replacing rib cartilage to total knee replacement (TKR). Moreover, the compatibility of PEEK with the existing implant materials, fillers and during surgery has also been discussed. These aspects have been investigated in the light of incredible mechanical and physicochemical properties of PEEK and its composites. 3D printing has provided the much needed assistance to develop and fabricate complex implants made up of PEEK based composites. The observations concluded that PEEK has shown promising characteristics to be a potential alternative for conventional implant materials. In dental applications, its light weight, biocompatibility and aesthetic pleasance has left patient healthy and satisfied. Similar satisfactory findings have also been observed when used in knee, hip, spine and other implants. PEEK can fulfill the long term demand of an ideal multipurpose material for biomedical applications. However, still there is a vast scope for future researches and works for the innovation and development of the techniques to make it more feasible and accessible, to ensure unhampered use of PEEK and PEEK based composites to benefit the society.

1. Introduction

From its introduction in late 1980s, Poly Ether Ether Ketone (PEEK) has evolved so much in the line to be a perfect biomaterial. In present times polyetheretherketone (PEEK) is valued among the most important engineering polymers. All due to its outstanding properties as high mechanical strength, better thermal stability, higher chemical resistance, and good wear resistance and anticorrosive nature. Apart from these PEEK possesses the most desirable characteristics to be the material of tomorrow which is its resistance to degradation. These properties are extremely desirable for applications in the biomedical, aerospace and automotive industry. As far as biomedical field is considered PEEK has been progressively used as a biomaterial for orthopedic implants and prostheses from the year 1987 [1,2]. PEEK does not persuade any mutagenic or cytotoxic activity as learnt from in to vitro biocompatibility tests. PEEK does not have any harmful reaction or releases any harmful constituents to the human tissues thus making it a bioinert material. Even after all these positive aspects of PEEK, the scope of improvement is still there and that too is because of the hydrophobic nature of PEEK which limits the cell adhesion and absorption of protein on the surface ultimately reducing the wound healing capacity on osseointegration. This is the very point where need of modification of PEEK generates to arouse cell attachment and proliferation. This modification we are talking about is done by combining PEEK with bioactive particles such as hydroxyapatite [3,4].This opens up a vast field for development of PEEK based composites. Now if we consider mechanical strength of PEEK for biomedical applications, it can be enhanced by reinforcing it with proper filler. For example carbon fibers reinforced PEEK have Young's modulus in the range of the cortical bone (i.e. around 18 GPa) while the neat PEEK have Young's modulus of about 3–4 GPa. This kind of flexibility in maneuvering the properties makes usage of PEEK much adaptable over conventional materials for implants. Let us consider the most used conventional material for implants i.e. titanium, need to know the Young's modulus of titanium is about 10 times higher than that of the cortical bone which is not desirable at all as this type of huge mismatch of properties could result in bone resorption and implant loosening. Furthermore, such mismatch can lead to overloading and may result in bone loss [5]. Therefore, PEEK

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composites could be possibly used in these applications concerning a material with an elastic modulus similar to that of the bone.

Apart from desirable Young's modulus, PEEK exhibit good impact strength, low vapour pressure, very good thermal stability, chemical resistance and excellent creep behavior. On a detailed note, the isothermal creep resistance (at room temperature) of PEEK is exceptional for both short and long term applications. However, creep compliance of PEEK increases by a large factor as temperature passes beyond the glass transition temperature (143 °C). In that case incorporation of reinforcement becomes necessary as unfilled PEEK is not suitable for use. Although in biomedical applications, usually, the operating temperatures are well below the glass transition temperature [6–11]. Now on a broader picture by the late 1990s, PEEK emerged as the leading high-performance thermoplastic polymeric material for replacing metal in the fields of implant especially in orthopedics and trauma [12–14]. PEEK was found resistant to be simulated in vivo degradation, including damage caused by lipid exposure. PEEK was first offered commercially in April 1998 as a biomaterial for implants (Invibio, Ltd.: Thornton Cleveleys, United Kingdom) [15]. Afterwards on being facilitated by a stable supply, research on PEEK biomaterials flourished and is expected to continue to advance in the future too [16]. Over the time various research studies has documented the successful clinical performance of PEEK and PEEK based composites in orthopedic and spine patients [17–22].

Tribology of PEEK composites has also investigated as biomedical material in flexible implants used for joint arthroplasty [23–26]. In order to further improve the implant fixation and durability, research on the compatibility of PEEK based materials with bioactive materials as hydroxyapatite (HAp), bioactive glass either as a composite filler, or as a surface coating has also come into focus in recent times [27–32]. As the developments on biomaterials are ongoing, PEEK and PEEK based composites are believed to be tailor made with a wide range of physical, mechanical, and surface properties, specific to the different types of implant applications. The main aim of this review article is to document the development of PEEK as a biomaterial and highlight the major advancement and break through along the time.

2. PEEK in medical field

2.1. 3D printed implants

It is a well-known fact that complexities of an implant make it difficult to manufacture, modify and develop for new possibilities. 3D printing seems a very good solution to tackle this problem but availability of 3D printing alone is not enough, the material of whom implant is going to be made should be 3D printable at least. Well, fortunately PEEK can be 3D printed, so making implants of premium features is no more burdensome. The Procedure for 3D printing of patient specific implants has been shown in Fig. 1. Although PEEK requires higher temperatures for melting, thus studies on 3D Printing of PEEK are very few [33]. However, some of them are very promising, in one particular study, 3D printing techniques have been able to easily fabricate complex shape PEEK implants by taking data of patient through CT/MRI scan [34,35]. It opens a wide range of opportunities with innumerable benefits like customization, development and producing a replica of bones and other human parts with precise shape and size.

These type of perfect 3D printed PEEK implants not only improve patient satisfaction and safety but also assist surgeons to quickly tackle the case of patients. Speedy recovery of patients is also ensured after using spot on implants [35–37]. Keeping these developments in mind, PEEK implants have become favorable over preexisting implants and are believed to flourish more. In upcoming years, with development in 3D manufacturing technology, PEEK materials are to make a significant mark in the fields of medical, dentistry, and associated areas [38–43]. The effectiveness of 3D printed PEEK implants can also be understood by the particular studies in which the costal cartilage prostheses were designed using PEEK. The cartilage prostheses are used in skeletal reconstruction of rib cage and are implanted as the replacement of natural cartilage which was removed during the extraction (resection) of tumour [Fig. 2].

The designed PEEK costal cartilage prostheses had mechanical properties almost same as natural costal cartilages. Even it has improved breathing as for the patient going through chest wall reconstruction. This feat was only be achieved due to the customized 3D printing of PEEK. These results clearly tells that PEEK 3D printed cartilage prostheses are very much superior to the previously produced titanium and Polymethyl methacrylate (PMMA) composite cartilages which surgeons are being using from late 1990s to recent times [44–52].

3D printing has provided PEEK a boost in its journey as a potential multipurpose biomaterial all set to replace the conventional implant materials. PEEK scaffolds are seeing a rise in demand as it is possible to have customized macropores in the implant structure ensuring ideal cell adhesion and proliferation which ultimately leads to bone regeneration. This feat has been achieved entirely due to the ability to obtain customized macropores by 3D printing of PEEK [49–56]. Although, it has been an uphill struggle for PEEK to be coherent with 3D printing. As far as PEEK is considered, the main 3D printing techniques namely Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM) have their issues. For SLS, it is the cost and material management, also coupler will be required for proper interaction between PEEK and bioceramics or other fillers. For FDM, it is the processing conditions due to the high fusion temperature of PEEK. Although it is believed that FDM is best technique for 3D printing of PEEK [57–64]. Newest developments on the 3D printing possibilities of PEEK and PEEK based composites are focused on improving design and parameters of FDM equipment. In one particular study, a high temperature chamber, nozzle with a heat collector module, and platform with two degrees of freedom is installed in a regular FDM printer. These new installments increase the interlayer bonding and distortion (warpage) in printed products was significantly reduced. Another approach in recent times is to develop a filament of

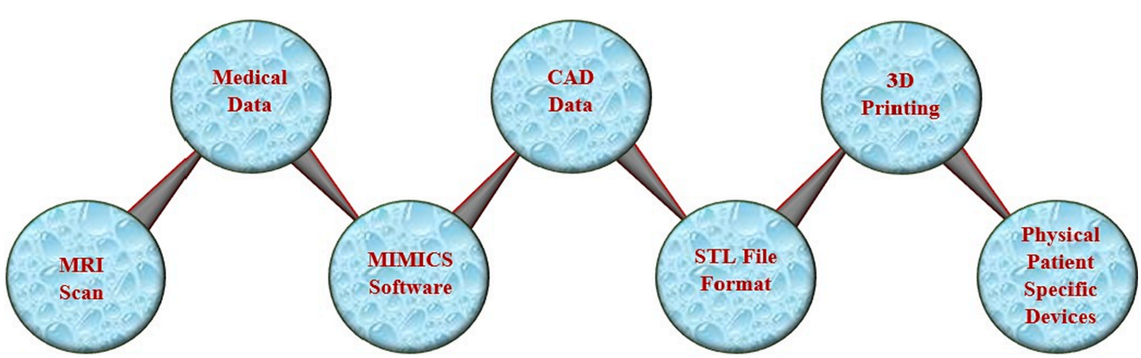

Fig. 1. Illustration of 3D printing digitization in biomedical field [33].

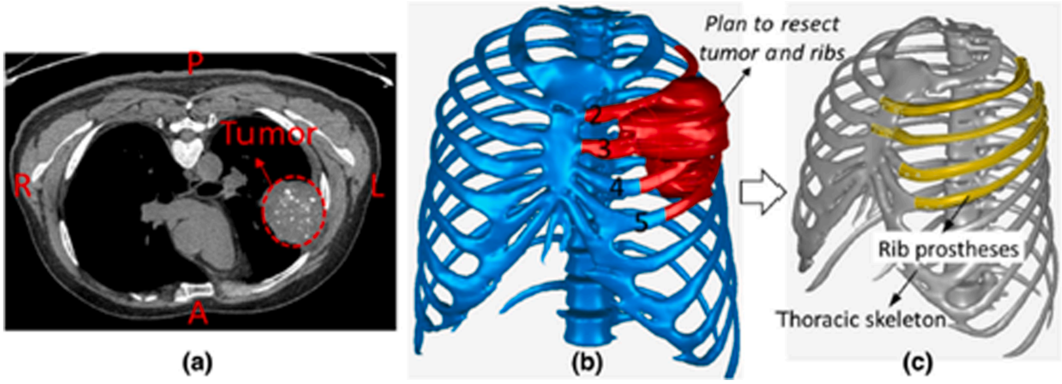

Fig. 2. Patient preoperative planning: (a) Tumour position in the CT image. (b) Resection plan of tumour and corresponding ribs. (c) Chest wall reconstruction using PEEK rib prostheses [51].

PEEK based composites such as carbon fiber reinforced PEEK filaments, Bioactive Amorphous Magnesium Phosphate (AMP) incorporated PEEK filaments. These prepared filaments can be printed through regular FDM printers with enhanced microstructure, bioactivity and osseointegration [65–69].On a concluding remark, future work should be focused on development and innovation of feasible and economic 3D printing techniques for PEEK. There is need to develop the fresh testing criterions and devices for the biomedical materials. Then only the vast commercialization of these products will be possible and the community will be benefitted.

2.2. Dentistry

Since ages metal alloys are being used for dental implants such as Titanium, Nickel, and Zirconia etc. Although in recent times, patients generally wants to avoid the metal implants as they are heavy and troublesome. They tend to feel alien to their mouth and don't really provide any aesthetic feature to it. So there been always a search going on for an optimum dental implant material. Under such circumstances, PEEK has emerged as potential material for dental implants. It is light weight, biocompatible and as being a thermoplastic, it can provide aesthetic looks as much as demanded. Apart from this, on the application part also, PEEK is superior to them. Most of the Dental implants are made up of titanium, but due to its higher elastic modulus (110 GPa) than the natural bone (10–30 GPa) it can cause overloading of the jawbone and can lead to its resorption. Here PEEK as biomaterial provides a very good alternative.

PEEK based composite dental implants have elastic modulus (3–4 GPa) in the range of jawbone. Recently, PEEK based dental implants are produced by additive manufacturing techniques. In one study, the FEM model of PEEK reinforced with carbon fiber (CFR) was studied to understand the stress distribution on using PEEK-CFR dental implant. The results showed that it prevented the cortical bone from high stress peaks as the stress distribution was uniform with PEEK implant [70–74]. However bio functionalization of PEEK may be required to enhance its bioactivity. PEEK can be functionalized by surface modification techniques such as sulphonation [75–78].This will further increase the utility of PEEK as a biomaterial for dental implants. In one case study, fixed partial denture framework was designed for a patient and 2, 3 and 6 month follow up was done. The patient shows very little plaque accumulation and was very much satisfied with the comfort and utilization. These encouraging results can be attributed to the light weight and biocompatible nature of PEEK [79].

So it can be believed that PEEK is definitely going to play a significant role in the field of dental implants. Although, further studies and research work will be required to ensure its long term usage and adaptability.

2.3. Other common implants of PEEK

The number of arthritis cases is on increasing trend from past two decades and so the increased demand of implants to cure them. The surgical treatment has become favorite among patients in recent years as it provides long term solution for the problem. This market is believed to reach a billion dollar mark by 2021. The constant research studies are on a run to perfect the implant and provide concrete remedy to the industry. Some of the existing implant materials are doing their job effectively some are not, however the former are very few. Most of them require modification and customization to the meet the demand of patients. This provides an opportunity to the newly emerging materials like PEEK to showcase their tremendous potential [80].This section will explore the application of PEEK in some significant field such as Knee replacement, spinal fixation, hip replacement etc.

Talking about the knee Implants, till now UHMWPE (Ultra High Molecular Weight Poly Ethylene) has been mostly used for total knee replacement or for flexion bushing in knee joint. UHMWPE has very low wear rate and very good biological properties as well if knee joint is considered in particular. However, UHMWPE's low creep resistance and lower fatigue limit cannot meet the expectations of future patients who want to do more active things. A study conducted on a specially designed knee joint simulator found out that PEEK based implants shows relatively similar wear rate and biocompatibility as of UHMWPE but better creep and fatigue resistance. However, it was also quoted that usage of PEEK-CFR bushings should be avoided as it showed higher wear rates (Fig. 3). So it would be better to pitch implants made of pure PEEK against the UHMWPE implants. Also in an in-vitro analysis based study, PEEK implant debris was found to be less inflammatory than the UHMWPE [80–85].These developments support the usage of PEEK in the knee joint implants and will further encourage the professionals to optimize the utilization of PEEK for it.

In spine implants, there are numerous studies which have mentioned the effectiveness of PEEK material. Conventionally, titanium cages are used as the spinal implants but the high elastic modulus and higher weight outperforms its utility. From surgeon's point of view, PEEK is a material which is biocompatible, has adequate temperature resistance, durable, corrosion resistant, and lightweight and is comfortable for the patient. Furthermore, unlike titanium PEEK does not possess any cytotoxicity and mutagenicity and also with PEEK implants, there is no risk of bone resorption as PEEK has elastic modulus similar to natural bone [17,93].

There are various research studies which have been done to compare the effectiveness of titanium and PEEK composite based implants in spinal surgery and its aftermath. The common finding is that the performance of PEEK is better than the titanium. The PEEK cages/implant shows higher fusion rate, better mechanical and biological performance [94,95]. Furthermore, in recent study biomechanical effects of PEEK-

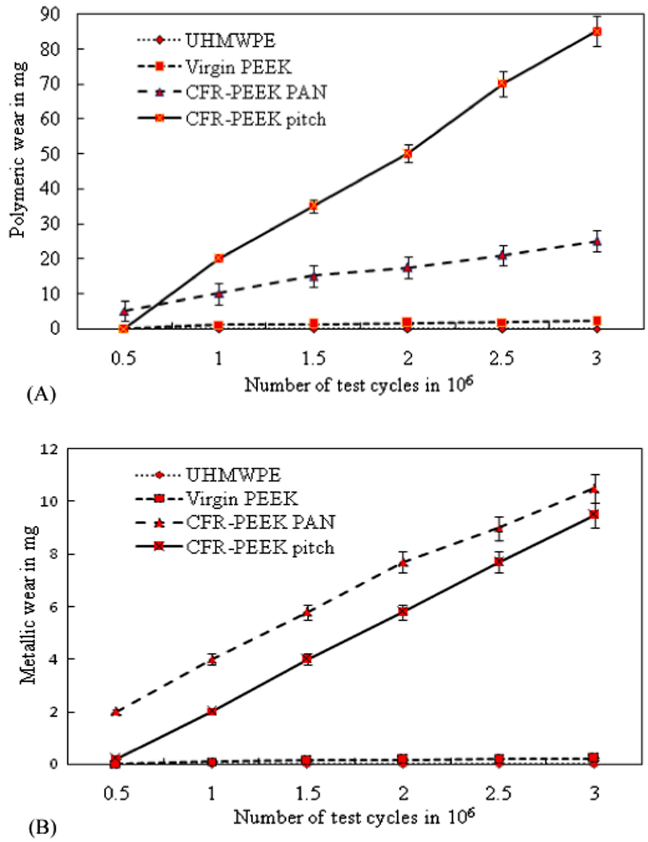

Fig. 3. Polymeric and metallic net wear: (A) Cumulative polymeric net wear of the different bushing materials and (B) metallic net wear of the CoCr axes articulating against the different bushing materials (with 95% confidence interval) [81].

CFR implants are compared with the titanium implants in osteoporotic spine model. The authors prepared pedicle screw/rod implants and these were tested under cyclic loading in ten human fresh-frozen cadaveric lumbar spines. The authors concluded that use of PEEK-CFR as alternative to titanium for osteoporotic spine is advantageous as the pedicle screw loosening was lower in PEEK-CFR implant when observed at microscopic level (Fig. 4) [96].

The application of PEEK in spinal treatment is not limited to just develop basic implants. In a unique study, PEEK implants (clips) were used post-surgical to prevent spinal fusion infection. It has been reported that regardless of extensive pre-surgical antibiotic treatments, about 10% of patients may develop infection after the spinal surgery. To counter this, an antibiotic reservoir was designed to release antibiotics

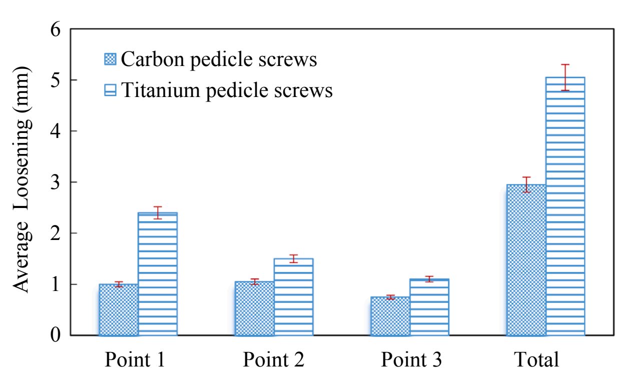

Fig. 4. Analysis of the cavities around the pedicle screws at 3 specified measurement points in a bar chart (with 95% confidence interval) [96].

after several days of surgery if infection occurs. This reservoir was a porous PEEK puck installed in PEEK clip. To release antibiotics, it was subjected to ultrasound which in turn ruptures the reservoir membrane and the antibiotics were released as illustrated in Fig. 5. This ultrasound-activated drug release system was adequate to treat post-surgical infection [97]. So, it is evident that use of PEEK in spine implants is both sensible and safe, thus provides a very good alternative to the spinal surgeons.

In India, more than one billion people are believed to affect from Osteoporosis. It is a condition in which mineral density of bone fall below the healthy levels. Osteoporosis is the key factor responsible for the severe arthritis in ageing people. Once the arthritis found hip joint, then it becomes very difficult and painful for the person to do basic activities of daily life.

As hip joint supports the entire upper body weight, so it requires urgent treatment. Surgical treatment of hip joint by replacing the joint is considered as feasible solution. The implant of hip joint require to have superior mechanical and biotribological properties as it is one of the most sophisticated joint of entire body. The conventional use of metal implants is not much supported from last few years as there is a possibility of implant loosening and release of wear particles will have an adverse effect on the body. Thus, polymeric implants are preferred for hip joint replacement and among these PEEK is much superior as it possess outstanding mechanical properties, chemical and heat resistance so giving overall better biomechanical performance [98–101]. Furthermore in one study, the tribology of PEEK-CFR composite for hip implant was investigated. PEEK-CFR wear resistance was enhanced by applying surface textures. The author concluded that application of dimples on the surface of PEEK-CFR implant material reduced the friction coefficient and wear rate thus, making it more suitable to use for hip implants [102]. Apart from this application, the use of PEEK and PEEK based composite has also been reported in other medical applications, some of them are summarized in the Table 1.

3. Compatibility of PEEK with other implant materials

For biomedical applications the compatibility of a material with other implant materials is also a desirable characteristic and to ace this feature material should be maneuverable. Compatibility of PEEK as a biomedical material with titanium, carbon fiber and bio fillers has been discussed in this section.

3.1. PEEK with titanium and its alloys

Application of PEEK with Titanium and its alloys had been observed in biomedical area. PEEK is seen compatible with titanium in very promising way. There are studies which show that usage of PEEK with Titanium yields better results such as in one study cellular structure of Ti6Al4V was produced by selective laser melting (SLM) technique and PEEK was pressure injected in the open cells and a multi material cellular structure of Ti6Al4V-PEEKwas obtained. It was observed that inclusion of PEEK protected the cellular structure of Ti6Al4V thus improving tribological performance of the structure. Further into the advancement of the study, this structure was found to have much more wear resistance. On comparing with conventional cast/forged materials used in implants, and Ti6Al4V cellular structures the mass loss was lesser by 40% and 62% respectively. The multi-material Ti6Al4V-PEEK cellular structure designed in these studies is potential alternative to fully dense metals presently used in orthopedic implant applications [103–106].Apart from SLM technique Laser surface structuring has also been used to prepare structure of PEEK and Ti6Al4V, in one such study the adhesion of PEEK with the metal surface of Ti6Al4V was studied. It was observed that the bond strength was improved and the Ti6Al4V-PEEK structure produced has good enough adhesion to produce mechanically stable joints [107].Thus it can be observed that PEEK is compatible with Ti and its alloys which are currently being used in the

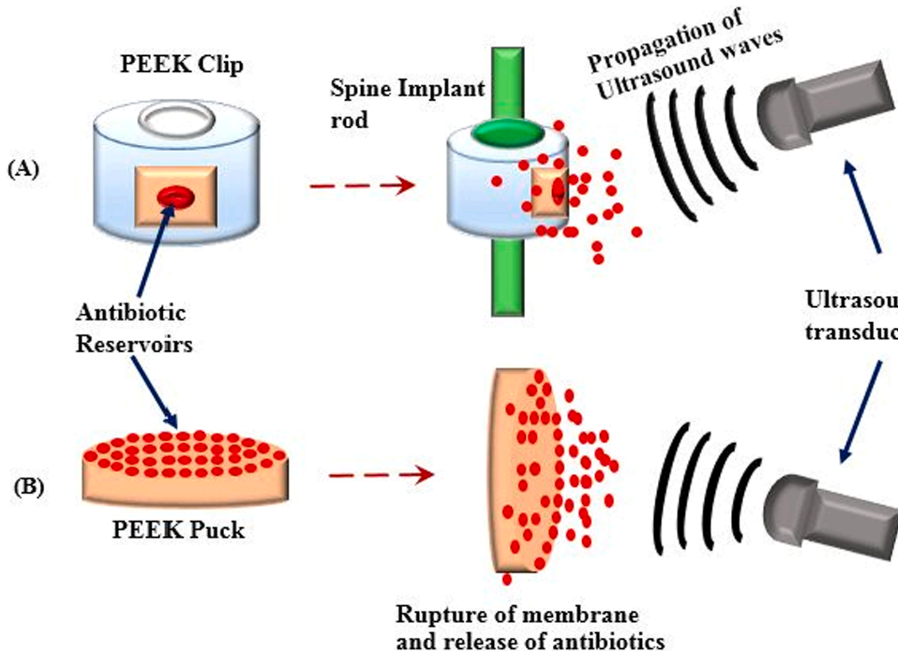

Fig. 5. Representation of loaded, sealed spinal clip (A) and porous PEEK puck (B) (elements not shown to scale). The clip (A) is shown with one-hole where the C-shaped area is for attachment to the spinal rod. The puck (B) has an array of pores. The coating on top of the reservoirs is insonated by US, causing rupture of the membrane to release the antibiotics [97].

Table 1
PEEK in various implant applications with their findings and outcomes.

Literature	PEEK composite Specification	Study details	Implant/ Application Area	Findings	Outcome
L. de Ruiter et al. [86]	Pure PEEK	PEEK and cobalt–chromium, using a finite element model of a TKA subjected to a deep squat loading condition.	Knee joint	Stress shielding was reduced to a median of 1% for the PEEK implant versus 56% for the cobalt–chromium implant.	+ve
S. Green and J. Schlegel [87]	Pure PEEK	PEEK used to make pump for intracardiac left and right ventricular assistance.	Cardiac	Potential alternative to heart–lung machine and less invasive than others.	+ve
J. Zhou et al. [88]	Pure PEEK	Total of 72 consecutive patients suffering from cervical degenerative disc diseases were treated surgically and were divided in 2 groups. A (40 patients, 64 segments) with PEEK cages and B (32 patients, 51 segments) with autogenous iliac crest graft, follow up was done for 18–24 months.	Cervical	PEEK cage emerges as substitute for fusion in patients with cervical disc disease as it can: • Effectively restore the cervical physiological curvature and the intervertebral height. • Facilitated radiological follow-up, cause few complications, and leads to satisfactory outcomes.	+ve
M. Leat and J. Fisher [89]	Pure PEEK	Valves were tested in specifically designed hydrodynamic simulator Valves dynamics were monitored using standard speed and high speed video cameras.	Heart Valves	Shows higher durability and smoother operation.	+ve
A. Thien et al. [90]	Pure PEEK	Studied retrospective records of patients who underwent PEEK and titanium cranioplasty to compare complication and failure rates between two types of implants.	Cranioplasty	The failure rate of PEEK cranioplasty (12.5%) was half than that of Titanium (25%).	+ve
M.M. Kim et al. [91]	Pure PEEK	4 patients with residual maxillofacial defects from trauma or surgical extirpation of neoplasms were evaluated at The Johns Hopkins Hospital, Baltimore, Maryland.	Face reconstruction	Easily workable, high durability.	+ve
C.S. Li et al. [92]	PEEK-CFR	Literature search was performed using MEDLINE and EMBASE from 1950 to February 2014.	Orthopedic implants	PEEK has excellent durability and required strengthIncreased recovery chance of patient in less time.	+ve

biomedical applications.

3.2. PEEK with carbon fiber

PEEK-Carbon Fiber (CF) composites are also used as implant biomaterials in orthopedics. CF is one of the most common fillers for composite materials. A matrix material must be compatible with the filler material to obtain uniform strength and load sharing. Studies have backed the usage of PEEK with Carbon Fibers, both PAN (Polyacrylonitrile) based and Pitch based. PEEK has been used with the both types of CF however, in one particular study it was observed that the mechanical properties of PAN based CF reinforced PEEK composite was superior than pitch based CF reinforced PEEK composite under monotonic and cyclic loading [108]. Utilization of PEEK-CF composites in biomedical had also been enhanced by various alterations such as surface modification of CF, nano-indentions on the surface of composite or using 3D braided carbon fibers. Each of these adaptations has specific advantages and applications. This is an ongoing process and new ways are being found out to improve the PEEK-CF composites [109–111].

All these findings are very promising and ensure the compatibility of PEEK with Carbon fibers. Further which type of carbon fiber should be used depends entirely upon the application and process parameters. Short carbon fibers possess good wear characteristics and can be processed with conventional composite manufacturing methods such as injection molding and extrusion. However, short carbon fibers reduce the ductility of PEEK which can lead to deterioration. While long fibers provide better mechanical properties than the short fibers as they can be braided in variety of ways. Although continuous fibers performance is much superior to the long and short fibers but their processing is less efficient and costly. Continuous fibers require the automated and advance manufacturing methods such as Additive Manufacturing and 3D printing for processing. Then, they yield to high performing composites for variety of applications [112–120]. The effect of various types of carbon fibers i.e. short, long and continuous fibers on mechanical properties of PEEK has been presented in Table 2.

3.3. PEEK with bioactive materials

Bioactive materials are responsive to their biological environment. They are non-harmful materials which help in bond formation between the implant and the surrounding tissues. Basically, there are two categories of bioactive materials namely osteoconductive and osteoproductive. These can be distinguished on the basis of bond formation and bone growth. The osteoconductive such as synthetic hydroxyapatite (HAp) and tri-calcium phosphate (TCP) ceramics, forms bond with hard tissues like the bone tissues and induces bone growth on the surface of the material itself. While the osteoproductive such as bioactive glass (BG), forms bond with soft tissues like gingival (gum) and cartilage and induces distant bone growth from the bone and implant interface [121].

PEEK has been used along with the bioactive materials as coating material for biomedical applications. In one study authors observed that the addition of β tri-calcium phosphate (βTCP) with PEEK have high biocompatibility and similar mechanical properties to that of the human bone. But, no such advantageous effects were evident for the osteoblast cells proliferation [122]. Another preferred osteoconductive bioceramic is HAp. HAp coatings have been in the field of implant from quite a time. HAp coatings have shown more survival time and observed to enhance the bonding between the implant and surrounding bones. However, insufficient osseointegration and difference of stiffness with surrounding bone tissues could cause stress shielding around the implant which can further leads to implant loosening.

Use of PEEK with HAp for coating reduces the threat of stress shielding and when combined this PEEK-HAp composite coating offers much similar stiffness as of the bone tissues. Studies have observed that incorporation PEEK with HAp have optimize the bioactivity and mechanical properties of the composite contrast with natural bone [123–126]. Apart from these, in one study a novel coating was created by incorporating bioactive glass micro-particles along with silver nanoparticles and PEEK Electrophoretic deposition (EPD) technique was used for coating. The antibacterial properties and biocompatibility were tested against the metallic implant. Superior antibacterial properties and cell attachment was observed in comparison to bare stainless steel. Although for various aspects further investigation was prescribed to seek a suitable coating composite [127].

4. Surface modifications of PEEK

The greater aim for surface modification and coating on any implant material is to generate an optimal surface for the application. It may be to induce osseointegration, primary stability of implant or to increase/limit cell proliferation according to the conditions after the implantation. It had been seen that rough and porous surfaces favorably influence above mentioned traits in a biomaterial. Thus as observed, surface modification is an important factor to extend the biomedical applications of a biomaterial such as PEEK. There are varieties of ways to modify the surface of PEEK such as coatings, functionalization by chemical treatments or by incorporation of gases [128,129]. These techniques are broadly classified in two categories as physical and chemical more or less in both of these methods the structure of surface is reformed at atomic level. Physical surface modification techniques involves surface treatment via physical means such as by flame, laser, electron beam, plasma and sputter coating to name a few. While in chemical surface modification techniques, surface modification is achieved by the chemical reactions. These chemical reactions are initiated on the surface by applying chemical solutions on the surface. That is why these methods are also referred as wet surface treatments or wet chemical processing. These involve techniques such as chemical etching and grafting. Grafting in particular is used for surface functionalization [130–133]. Among all these techniques, Plasma spray coatings are preferable as they provide high roughness and porosity. Plasma surface treatments provide better topographical modification for biomedical applications as they induce better surface wettability and increased surface area when compared to simultaneous chemical etching processes. It has evidently observed in the literature that Plasma sprayed titanium, HAp, coatings have enhanced the response of osteoprogenitor cells on PEEK surface. However, after the plasma spray the generation of residual stresses on the implant surface has been seen to diminish the flexural fatigue strength of PEEK. Thus, Plasma processes are incorporated along with other chemical coating processes such as chemical etching. It has been observed that after incorporation of surface treatment processes PEEK shows better surface properties [134–138].

Further, Plasma process when preceded by sandblasting had been proved an optimum surface treatment procedure for PEEK. As it has positive effect on shear bond strength and adhesion of PEEK implants

Table 2
Effect of different types of carbon fiber reinforcement on mechanical properties of PEEK.

Literature	Fiber type	Composite preparation method	Fiber Composition	Outcome
W. Zhao et al. [114]	Long	3D needle punched	In the range of 30% to 60% by weight	• Tensile strength increase in the range of 3 times to 4.5 times respectively with weight % of fibers. • Bending strength increases in the range of 2 times to 3 times respectively with weight % of fibers.
N. van de Werken et al. [115]	Continuous	Additively manufactured	42% by volume	• Tensile strength increases up to10 times when tested at 250° C. • Bending strength increases up to 6.5 times at 250 °C.
D. Garcia-Gonzalezet al. [116]	Short	Injection molding	30% by weight	• Tensile strength increase up to 2 times. • Compressive strength increases up to 2 times.
K. Fujihara et al. [117]	Continuous	Compression molding (Fibers were micro braided)	41.6% by volume	• Bending strength increases up to 7 times.
A. Avanzini et al. [118]	Short	Commercially available extruded specimen were used	10% and 30% by weight	• Fatigue strength increase upto1.5 times for 30% sample while reduced to half for 10% sample.
M. Luo et al. [119]	Continuous	3D-printed	38.27% by weight	• Bending strength reaches up to 3 times.
B. Chang et al. [120]	Continuous	Additively manufactured	59% by volume	• Bending strength increases up to 9 times. • Tensile strength increases up to 15 times.

[139,140]. Some other novel coating methods for PEEK has also been reported in literature such as Crystalline HAp coating by chemical deposition [141], bioactive glass–chitosan coating by the combination of sand blasting and acid etching [142]. These novel methods have yielded positive outcomes in order to enhance the biomedical usage of PEEK. In a unique study, coating of bioactive amorphous magnesium phosphate (AMP) was done on the PEEK surface by using microwaves. The AMP coating solution of is initially applied on the PEEK discs than it was irradiated in a microwave oven for 5 min and the process was repeated one more time to ensure uniformity. This deposited bioactive AMP coating promoted the bioactivity of PEEK such as cell attachment which is beneficial in orthopedic and dental applications [143].

5. Conclusions

The aim of this review article is to provide an insight on the developments and advancements of PEEK as a bio-medical material. The different domain areas of PEEK in medical field such as dentistry, knee implants, spine implants, crainoplasticity, hip replacement, anterior plate fixation etc. have been taken into consideration and discussed on the basis of reported studies. The following conclusions have been drawn from this review work:

- 3D Printing techniques have allowed the production of complex and precise implants of PEEK based composites. This has augmented the outreach of PEEK as a biomaterial. Recent developments are targeting to increase the adaptability of 3D printing techniques for a wider range of applications.
- In Dentistry, PEEK has been seen as an alternative material to the metallic implants. PEEK based dental implants are lightweight, biocompatible, and have more aesthetic appeal. However, much more significant role is expected in the field of dental implants.
- Orthopaedic implants of PEEK and PEEK based composites are a success in terms of mechanical and biological performance. PEEK based implants have shown similar properties as of the natural human bones. The adaptability, durability and biocompatibility of PEEK is above par as observed in the various hip, spine and knee implants.
- PEEK is compatible with bioactive materials such as HAp, bioactive glass etc. It is used to maneuver the mechanical aspects of bioactive materials in the range of natural bone tissues.
- Plasma surface treatments along with other coating techniques have been seen as an effective tool to enhance the bioactive properties such as cell attachment, shear bond strength etc. of the PEEK implants.

6. Future outlook

The present review article summarizes the findings related to the developments of PEEK as biomedical material. It has been confirmed from the conducted literature that PEEK has evolved as a brilliant material in medical applications. However, there is always a scope of improvement. Some of the future outlooks have been identified for further investigations of PEEK such as to utilize the potentials of PEEK as an alternative to conventional metallic implants, improving the osseointegration capability without inducing residual stresses after the topographical treatments of the PEEK implants. Another diverse aspect which requires further advancement is that3D printers available in market nowadays are specifically designed for certain applications. They are expensive and not adaptable to research and application work simultaneously. Thus, more efficient, feasible and economical methods should be developed to ease the fabrication of PEEK by 3D Printing and other additive manufacturing techniques. Moreover, to ensure the prolonged services and adaptability of PEEK as biomaterial, future studies and researches should also focus on post-surgical follow ups.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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