Clinical Epidemiology and Global Health xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Clinical Epidemiology and Global Health

journal homepage: www.elsevier.com/locate/cegh

Polyether ether ketone (PEEK) and its 3D printed implants applications in medical field: An overview

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ARTICLE INFO

Keywords:
3D printing
Additive manufacturing (AM)
Applications in medical
Implants
Medical
PEEK

ABSTRACT

Background: Extensively studied research articles on Polyether ether ketone (PEEK) in “medical” and “PEEK 3D printing in the medical field” to identify a direction of the development and identify critical applications in medicine.

Materials and methods: This is a literature-based study of research articles listed in Scopus. A literature review & bibliometric analysis is done to achieve the research objective.

Results: Searching keywords as "PEEK" "medical" through Scopus identified 426 research articles and searching “PEEK” “medical” “3D printing” identified ten articles. This study identifies that PEEK is a suitable material that helps innovation and helps to solve different surgical and medical problems. Analysis of the Scopus data depicts an increasing trend in the medical field, especially the application of this material. Much research is done on PEEK in medical, but there is very less work reported on PEEK 3D printing in medical. 3D PEEK implants are preferred in medical for requirements of extensive customisation. This technology caters well to the manufacturing of prosthetics, artificial bone, heart & its parts and other human parts. Finally, twelve important applications areas are identified in medical.

Conclusion: PEEK has somewhat bone like properties. This material can be well used in 3D printing technologies to help fulfil various challenges of the medical. In medical, PEEK materials foresee different surgical application as it can replace titanium and ceramic implants. The need is to explore the use of PEEK in different surgeries of orthopaedic, spine, maxilla-facial, cranial and others 3D printing manufactures complex design implants as per requirement of a patient with an exact match. This material is also applicable for cardiac surgery like manufacturing of heart valve prostheses and leaflet heart valves. PEEK material is hard, lightweight, stiff and is a robust polymer while having satisfactory wear properties that help implants with an extended life. In dentistry, PEEK implants have also the potential for use in tooth replacement. It seems somewhat cost-effective to fulfil innovative medical requirements with comparable wear and mechanical strength.

1. Introduction

Polyether ether ketone (PEEK) is a thermoplastic organic polymer, that is becoming increasingly popular due to its applications for the manufacturing of medical tools, devices, implants and associated types of equipment. PEEK, was developed by US aerospace industry in the late 1970s. Its medical usage started in the 1980s and followed in 1990s for clinical studies and manufacturing of implants and has properties of stability at high temperature.[1,2]

Nowadays, a few medical professionals are using PEEK implants. These implants have a wide range of unique qualities. 3D printing technologies are applicable for low volume production to fulfil the customised demand of surgeon/patient.[3] 3D printing technology is known as additive manufacturing (AM). Mostly Fused Deposition Modelling (FDM) printers are preferred to print PEEK material. In this technology, the material used is in the form of a wire.[4–6]

3D printing technologies allow the construction of complex design geometry PEEK implants. However, it is challenging to manufacture them by traditional manufacturing technologies.[7] 3D printing can manufacture lighter weight implants and reduce inventory as implants are made as per individual demands. It manufactures a 3D model by joining of material layer by layer, there by producing a unit 3D model with a lower cost without the requirement of any tooling. This technology is rapidly growing to fabricate patient-specific implants of bone,

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https://doi.org/10.1016/j.cegh.2019.01.003
Received 4 November 2018; Received in revised form 17 December 2018; Accepted 3 January 2019

prosthetic, heart and its components.[8,9]

In medical, the main aim is to maximise the power-to-weight ratio and create development and innovation by using the high-performance material. PEEK is a high-performance polymer which used for manufacturing of medical implants and devices which has a high capability of load bearing. Implants are bone-friendly and more compatible than metal implants.[10–12] For the manufacturing of spinal cages, it has a significant role to solve various other problem of complicated surgery. Analysed a spinal rod manufactured by PEEK materials and found it to be beneficial than the conventional metal rod.[13] It has a melting temperature at around 343 °C. It has excellent wear and abrasion resistance and less coefficient of friction. In medical, this material has various demanding applications.[14,15]

2. What is polyether ether ketone (PEEK)

PEEK is a top-notch organic thermoplastic polymer; it is colourless and can be used suitably for modelling accurate parts with good quality. It has broad application in medical, dentistry, aerospace, automotive and other associated areas. These materials are semi-crystalline thermoplastics having excellent mechanical properties.[9,11] It shows excellent strength, dimensional stability and stiffness and sustains high temperature which replaces metal. Without the requirement of lubrication, it has high wear resistance and low coefficient of friction. Due to the robustness of this material, it is used to manufacturing demanding products such as medical implants, piston parts, bearing, pumps, electrical cable insulation and compressor plate valves. It is also applicable for ultra-high vacuum applications. This material is useable where there are requirements of continuous high temperature, and it has a melting temperature at 343 °C.[16,17]

3. Properties of PEEK implants

PEEK materials show excellent mechanical properties with Young's modulus of 3.6 GPa and tensile strength between 90 and 100 MPa. Implants manufactured by PEEK have a unique combination of properties such as temperature resistance, excellent chemical wear and numerous processing capabilities.[18–20] Table 1, provides the various properties of PEEK that make it suitable for medical purposes.

4. Research objective

Medical applications required implants and parts which are manufactured through different technologies and are putting into the human body. Now a day, implants of metal like titanium oxide, cobalt steel and stainless steel are used, they have two significant issues of weight and customisation. The principal objective of this paper is to find out the research status of PEEK when it is being used in medical and 3D printing. The primary research objectives of this paper are:

I. To identify the research status on PEEK as used in medical and PEEK 3D printed parts used in medical.

II. Formalising a process to manufacture PEEK implants through additive manufacturing and comparing it with traditional manufacturing processes.

III. Identifying the primary advantages and disadvantages when a PEEK part is 3D printed and made through the traditional process.

IV. Identifying the major application areas of PEEK in medical

This research is to be conducted by review process to fulfil above research objectives.

5. Basic requirements of the medical field as fulfilled by PEEK implants

PEEK assists innovation, due to its required strength, durability and stiffness. It becomes popular due to its better elasticity as similar to human bone.[1,21,22] Diverse requirements fulfilled by PEEK implants in the medical field are as under:

➢ Speedy recovery of patients

PEEK manufactured implant help speedy recovery of the patient body after the surgery.

➢ Accuracy

Implants manufactured by this material have better accuracy and fit precisely in the patient body.

➢ Easily implemented during surgery

Table 1
Basic properties of PEEK implants.

S. No	Property	Description
1	Excellent biocompatibility	• PEEK material is biocompatible • It easily interacts with the human body and increases the success rate for medical applications such as replacement of prosthesis, stents, and other medical implants • Use of nano-material helps PEEK implants to perform required function concerning medical therapy that increase the performance of patient during surgery • These implants can implement in the patient body without causing deleterious changes
2	Less weight	• Implants manufactured by PEEK material have less weight as compared to other traditional material being used for the same purpose • These implants provide a natural look and feel with excellent safety and characteristics • Lightweight PEEK implants enhance comfort, safety and quality of life of the patient
3	Good mechanical properties	• PEEK implants can withstand and not deform during a load of the whole body • It provides constant function during the variation of the temperature of the body • It has high rigidity, modulus stability and chemical resistance
4	High tensile strength	• These implants have high tensile strength under the action of the load • Implants have maximum tensile strength can withstand before breaking which is beneficial for the human body • Its tensile strength is 90–100 MPa
5	Low moisture absorption	• This material has a low moisture absorption • It needs less drying time which is suitable for a medical purpose
6	High flexible	• PEEK material is capable of bent easily without breaking • Has better flexibility
7	Suitable for high vacuum or pressure applications	• Used in medical for the manufacturing of pressure or vacuum devices • It increases the performance of devices that have highly resistant to most chemicals
8	Stable high temperature	• PEEK materials stable high temperature which is beneficial for medical and engineering applications • It melts at 343 °C which have a high melting temperature as compared to most of other thermoplastics • It has good toughness, low toxicity and excellent abrasion resistance.

As implants are made as per individual specifications and are used easily for surgery.

➢ Flexible

These materials are having higher flexibility such as manufacturing of cardiac valves for the patient suffering from heart diseases.

➢ Efficiency

Implants can assist the load of the body that increases the efficiency of the patient.

➢ Increase success rate of operation

During operation, these implants increase the success rate of operation due to its excellent material properties.

6. Research status on PEEK in medical and PEEK 3D printing in medical

6.1. Research status on PEEK in medical

Research on PEEK in medical is continuously increasing. Scopus database is searched through keywords "PEEK" "medical" and identified 426 articles from 1976 to November 2018. There was only one article in 1976. Then in 1979, two articles were published, and in the years 1981, 1985, 1986, 1987, 1988 and 1990 one article each year. In 1991, five articles published. In 1992, 1992, 1994 and1996, there was decrement of publication, in these years only one article was published. In 1997 (two), 1998 (four), 1999 (three), 2000 (two), 2001 (five), 2002 (five), 2003 (twelve), 2004 (five), 2005 (ten), 2006 (ten), 2007 (eighteen), 2008 (eighteen), 2009 (nineteen), 2010 (twenty one), 2011 (seventeen), 2012 (thirty one), 2013 (thirty), 2014 (thirty four), 2015 (forty five), 2016 (thirty three), 2017 (forty) and till November 2018, forty two articles are published so far. So, we observed a rapid increment of publications in the past ten years.

Different journals are publishing research articles on 'PEEK in medical', and out of these journals, the top journal is "Surface and coatings technology" that has published eight articles. "Materials Letters" and "Materials science and engineering C" published seven articles each. "Applied surface science", "International Journal of nanomedicine", "Nanomedicine", "Medical device and diagnostic industry" and "Spine" published five papers each. "Chinese Journal of tissue engineering research", "Chinese Journal of tissue engineering research", "Colloids and Surfaces biointerfaces", "Journal of applied polymer science", "Journal of materials science materials in medicine", "Key engineering materials", "Plasma processes and polymers", "Plastics technology", and "Wear" journal published four articles by each. Rest journals and sources also have a significant contribution in this field.

Materials Science field provides a maximum contribution of 27%. Secondly, 21% contribution is from the medical field. Whereas 'Engineering' contributes 12%, 'Physics and astronomy' 6%, "Chemical Engineering" also contributes 6%, "Chemical Engineering" again contributes 6%, 'Business, Management and accounting' contributes 4% and there is 12% contribution is given by "other fields" that includes Computer Science, Neuroscience, Pharmacology, Toxicology and Pharmaceutics, Dentistry, Psychology, Social sciences, Business, Management and accounting, Nursing, Arts and humanities, Earth and Planetary Sciences, Mathematics, Energy, Environmental science, Health professions, Agricultural and biological sciences, and Veterinary.

6.2. Research status on PEEK 3D printing in medical

There are decidedly fewer research articles published in "PEEK 3D printing in medical". Searching with keywords as "PEEK" "medical" "3D printing" from Scopus; identified only ten articles. The first article in this area was published in 2014. In 2015, two articles were reported, and in 2016, three articles were published. In the year 2017, only one article published, and in 2018 to November, three articles are published so far.

Different journals published all these articles. Journals "Chinese journal of lung cancer", "Chinese Journal of tissue engineering research", "Composite structures", "Gaofenzi cailiao kexue yu gongcheng polymeric materials science and engineering", "Journal of materials science materials in medicine", "Journal of the mechanical behavior of biomedical materials", "Materials", "Materials and design", "Materials research innovations", "Virtual and physical prototyping" published one paper by each.

In area wise contribution of research, here we identified that "Engineering" and "Materials science" field have the equal contribution of 29% by each. Biochemistry, genetics and molecular biology contribute 13%, Chemical engineering (9%), Medicine (8%) and "Computer science", "Mathematics", "Physics and astronomy" fields have the equal contribution of 4% by each.

From Scopus data, it has been analysed that research is reported on PEEK in medical, but there is less paper published in PEEK 3D printed in medical. In upcoming years, the PEEK material application may become commercially viable and acceptable in the medical field.

7. Processes of making PEEK implants by the traditional manufacturing process and additive manufacturing process

7.1. Implants manufactured through the traditional manufacturing process

In medical, manufacturing of personalised implant is the ultimate goal. In past years, only subtractive manufacturing methods like CNC and other traditional machines are used to manufacture PEEK implants.[23,24] Fig. 1 shows the steps used to create PEEK implants by the traditional manufacturing process.

Fig. 1 shows the steps used to create PEEK implants using a

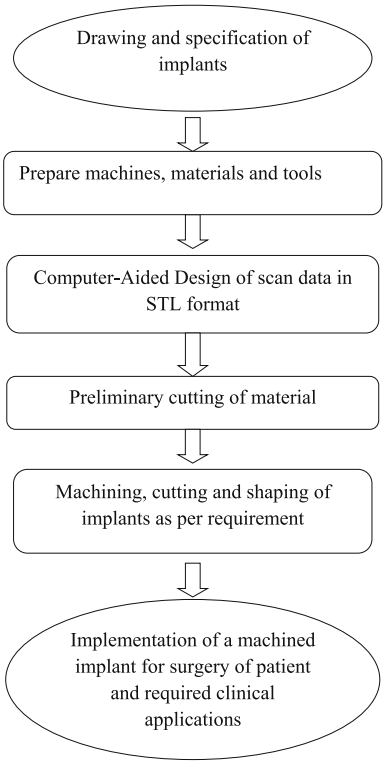

Fig. 1. Implants manufactured through the traditional manufacturing process.

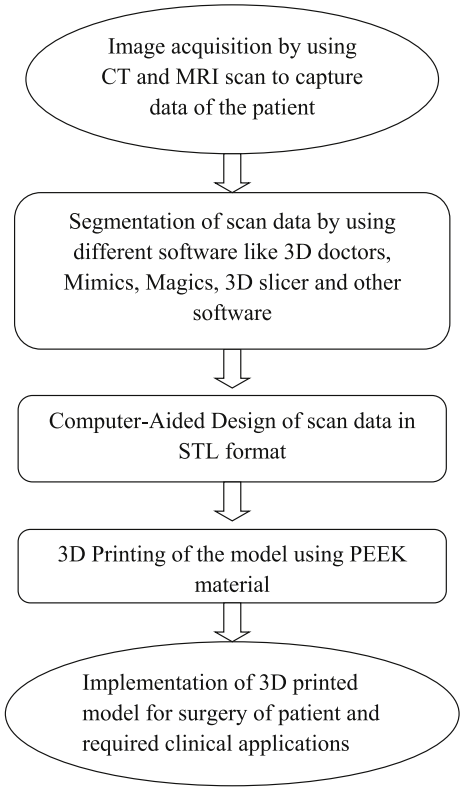

Fig. 2. Implants manufactured through the traditional manufacturing process.

traditional manufacturing process. Medical data is varying from patient to patient, so there is a requirement of customisation. This technique has some limitation such as time-consuming, material wastage, expensive and does not provide fit implants as per patient match. So there is a requirement of additive manufacturing that easily create customised implant as per patient match in less time.

7.2. Implants manufactured through the additive manufacturing process

Additive manufacturing technologies are now available to print patient-specific implants, devices, and instruments as per requirement. This technology easily fulfilled various challenges as compared to the traditional manufacturing method. Also, PEEK is used in 3D printing for manufacturing of complex design implants which is readily acceptable by the human body.[25,26] PEEK is the highly useful material for medical to produce implants as compared to other materials.[27,28] Now a day's doctors and surgeon are using 3D printing technologies for the production of PEEK implants as per required design. Fig. 2 shows the various step used to create implant through additive manufacturing.

PEEK 3D printed implants provide higher design freedom with a lesser waste of raw material. These implants reduce the failure rate of the patient and are bone-friendly. PEEK 3D printing technologies efficiently fulfil this customised requirement of the patient. Computer tomography (CT) and Magnetic resonance imaging (MRI) are used to obtained data of the individual patient and then converted into 3D CAD data by using different software in standard triangulate language (STL) format. This 3D CAD data is easily printable by 3D printing technologies.[29] These 3D printed PEEK implants are further tested and implemented for the surgery of a patient.

8. Fundamental advantages and disadvantages of 3D printing over traditional manufacturing method as for manufacturing of PEEK implants

3D printing technologies provide different steps to create medical implants with the help of CT and MRI scan. 3D printing technologies are readily applicable to the design and development of an implant that also creates good co-operation between patient and surgeon.[30] The primary advantages of 3D printing over traditional manufacturing method for the manufacturing of PEEK implants are discussed in Table 2.

9. Application areas of PEEK in the medical field

In the healthcare industry, PEEK provides features such as biocompatibility, durability and excellent resistance. It is best and suitable material for pivotal applications such as orthopaedic implants, spinal implants, surgical equipment and dental equipment.[47,48] PEEK implants devices are on rising in recent years due to its suitability of contact with the human body and is also incorporated into the manufacturing of active implantable devices. In the last few years, it is accepted widely in the human body over other traditional plastic and metals. Table 3 describes twelve crucial application areas of PEEK in medical.

In medical, there is a requirement of innovation to save the life of the patient.[72,73] It is commonly used for the manufacturing of orthopaedic implants due to its modulus similar to bone. PEEK tubing is used for medical applications due to its high vacuum and pressure holding capability. This material is more useful than aluminium, steel, glass and other polymers. PEEK is a hard polymer, stiff and robust polymer having suitable wear properties.[74] PEEK is also useful for repairing soft tissues and grafts.

10. Discussion on findings

PEEK materials are applicable for different surgical applications in the medical field. It can replace titanium and ceramic implants which are being used for different surgeries of orthopaedic, maxilla-facial, cranial and spine. These materials are tough having the capability to withstand high temperatures. It creates innovation for spinal arthroplasty devices. PEEK is used for reconstruction of the customised face of the individual patient with a required strength, durability and stiffness. Now, 3D printing is also available to manufacture implants with exact dimensioning as per patient requirements. It has more benefits over traditional manufacturing methods. 3D printing produces implants with higher accuracy that reduces the risk of surgery and maximises the success rate of operation. It converts innovative ideas of doctors and surgeon into reality. It is also applicable for cardiac surgery like manufacturing of heart valve prostheses, leaflet heart valves and stents. It is efficient for the cardio patient to provide comfort as it not provided by other materials. Another application of PEEK material in cardiology is the manufacturing of rotor of a micro axial pump. In dentistry, PEEK implants are used for tooth replacement. The application of PEEK is becoming popular due to its better elasticity as similar to natural bone.

11. Future scope

In future, PEEK may become suitable material to manufacture implantable medical devices having efficient output and can fulfil the innovative requirements. Due to its higher capability of patient comfort, it provides an essential improvement in medical and other associated fields. It creates a disruptive effect and increases the performance of surgery. Research on this material will increase. It will replace conventional material for fabricating medical implants. It will manufacture any biomedical splint, stents, and orthodontics devices as per patient requirement of strength. In the future, the applications of this material will create possibilities in the medical field. Doctors and surgeon adopt PEEK for the best treatment of the patient. It will create development in medical and become more common in other fields. This provides better surgery of patient and helps to create patient implants. In future, AM technology will help easy manufacture of customised/

Table 2
Basic advantages and disadvantages of 3D printing over traditional manufacturing method for the manufacturing of PEEK implants.

S No	Advantages	Description	Limitation	References
1	Design freedom	• Computer-aided design software is required to create a new design • 3D printing technologies have the flexibility to produce any implants of complex design • Innovative design improve performance and flexibility of 3D printed PEEK implant	• Requirements for educated and highly skilled human resources	Honigmann et al., 2018[30]; Popescu et al., 2018[31]; Blanco et al., 2018[32]; Haleem et al., 2018[33]
2	Customisation	• Manufacture any customised product with shorter time • Efficiently fulfil the requirement of implants as per individual patient match	• Costly in case of mass-production	Vaezi and Yang 2015[6]; Dahake et al., 2016[34]; Yap et al., 2017[35]
3	Save cost	• PEEK 3D printed customised implants has less manufacturing cost • Save tooling cost during the manufacturing of implants because the whole product is manufactured in one time	• Only suitable for customised implants	Basgul et al., 2018[9]; Scolozzi et al., 2007[36]; Negi et al., 2014[37]
4	Low wastage	• There is a very low wastage of raw material because in this process material is added layer by layer. • In the machining process, there is much wastage of raw material because the material is removed from the workpiece to convert into final product • Produces lightweight models according to input materials that improve the functionality and durability of medical implants • In some AM technologies, the raw material is recycled, thereby reduction in the final cost of the product	• Material cost is high	Hieu et al., 2005[38]; Chimento et al., 2011[39]; Javaid and Haleem, 2018[40]
5	Reduce design and development time	• Reduces the modification and up-gradation time of product/implant as compared to the traditional process • Innovative designing and development through 3D printing to help improve functionality and aesthetics	• Requirements for highly skilled designer and costly software	Begines et al., 2016[41]; Chiu et al., 2016[42]; Haleem and Javaid 2018[43]
6	Less requirement of labour	• As compared to traditional manufacturing process there is a lesser requirement of labour • 3D printing technology is controlled entirely through software, the only command of printing is required, and part gets manufactured automatically	• The high cost of AM technologies	Tiwari et al., 2015[44]; Paul et al., 2018[45]
7	Exact fit implants for the patient	• 3D printing technologies manufacture implants as per patient match • 3D implants are an exact fit to the patient body	• Sometimes not able to achieve the same accuracy of the implant as compared to traditional manufacturing process such as CNC	Dahake et al., 2016[34]; Cabitza et al., 2018[46]

The primary requirement of PEEK 3D printed implant arises when standard implants are not fitting correctly. This technology has various other benefits such as customisation, innovative design, materials saving and innovative development of medical tools and devices. By using these implants, a surgeon can now perform a better operation with higher comfort to the patient.

Table 3
Application areas of PEEK in the medical field.

S No	Application areas	Description	References
1	Orthopaedic surgery	• Due to high strength, PEEK is used for various orthopaedic applications like hip replacements, hip resurfacing and construction of femoral component • Artificial implant of bone assist load of the body of the patient	Steinberg et al., 2013[49]; Faldini et al., 2011[50]; Pace et al., 2004[51]
2	Medical tubing	• PEEK is suitable for medical tubing applications • It has high purity, organic polymer with good resistance • It is also having flexural modulus and requisite tensile strength • PEEK tubing is used medical where high rigidity required	Monich et al., 2017[52]; Johansson et al., 2014[53]
3	Spinal implants	• For spinal implants, PEEK offers many advantages as compared to metal. • Include modulus close to bone which is the ultimate solution for the surgeon	Kurtz and Devine, 2007[54]; Barkamo et al., 2013[55]
4	Spinal fusion	• Applications of this material are expanded significantly for the manufacturing of intervertebral fusion cage • It is a critical alternative of implants manufactured by metals	Kulkarni et al., 2007[56]; Wang et al.,2010[57]; Grupp et al., 2014[58]
5	Spinal arthroplasty devices	• PEEK materials are used innovatively for spinal arthroplasty devices • These are extremely hard and capability to withstand high temperatures	Wang et al., 1999[59]; Niu et al., 2010[60]; Guo et al., 2018[61]
6	Bone screws and pins	• For the manufacturing of screws and pins, PEEK has excellent capability in required strength used to hold the bone in place. • Increase recovery chance of patient in less time	Li et al., 2015[62]; Fujihara et al., 2003[63]
7	The smooth motion of the spine	• For developing a treatment in spine surgery, there is a requirement of smooth motion of spine implant. • PEEK are the key material that helps to enhance the movement of the spine	Guo et al., 2018[61]; Selim et al., 2018[64]
8	Minimally invasive fusion surgery	• Used for innovation in spine surgery with minimally invasive fusion • It also reduces nerve root retraction and tissue dissection	Stratton-Powell et al., 2016[65]; Selim et al., 2018[64]
9	Used for Stabilisation devices	• PEEK materials are used for manufacturing of unique instrumentation for medical • Used for soft-stabilisation and flexible-stabilisation for complex treatments	Monich et al., 2017[52]; Nieminen et al., 2008[66]
10	Face reconstruction	• Applicable for the reconstruction of the face of the individual patient with high strength, durability and stiffness • These implants are easily workable, non-porous for facial reconstruction.	Scolozzi et al., 2007[36]; Kim et al., 2009[67]
11	Heart valve and stents	• Used for the manufacturing of heart valves and stents having high durability • Efficient for the cardio patient during surgery and performed high comfort as compared to other materials	Zhou et al., 2011[68]; Guo et al., 2018[61]
12	Dental implants	• In dentistry, PEEK also shows an excellent contribution to the manufacturing of missing teeth to enhanced comfort of the patient. • Used for construction of partial dentures, crowns and bridges due to its light weight and strength	Schwitalla et al., 2015[69]; Sinha et al., 2017[70]; Lee et al., 2012[71]

designer PEEK implant. It provides close collaboration between the surgeon, doctors and patient. In future, it may also make development in the medical field such as tissue engineering. It provides cost-effective and innovative parts with requisite wear and mechanical strength. It improves the biocompatibility of load-bearing implants. 3D printing will be useful for manufacturing of different PEEK implants of head, neck, skull, jaw, face and other associated bones.

12. Conclusion

In the field of medical, fabrication of a customised implant is the primary goal. For patient-specific implants and devices, PEEK material seems a satisfactory material to fulfil the requirement of medical. It is colourless, and the models manufactured by them are suitable for various medical applications. 3D printing technologies easily fabricate complex shape PEEK implants by taking data of patient through CT/MRI scan. It opens a new market which has various benefits like customisation, manufacture a replica of bones and other human parts with exact shape and size. These 3D manufactured PEEK implants improve patient satisfaction and safety. The surgeon can quickly tackle the medical problem of the patient. In the Orthopaedic field, it is applicable for manufacturing of load-bearing implants with similar properties as of human bone. PEEK is an advanced biomaterial which manufactures lesser weight implants to provide satisfaction to the patient with efficient performance. PEEK materials match with human body fluids. It has outstanding properties like biocompatibility, non-toxicity, osteoconductivity, and non-inflammatory nature. It is used for a wide variety of applications in bone tissue engineering, post teeth bleaching, spinal implants, Joint replacement and restoration of periodontal defects, therefore, helping improved patient outcomes with higher reliability. In upcoming years, PEEK materials to create a higher impact on various fields of engineering, medical, dentistry, and associated areas.

Conflicts of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cegh.2019.01.003.

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