วารสารการพยาบาล สุขภาพ และสาธารณสุข
ปีที่ 2 ฉบับที่ 3 กันยายน - ธันวาคม 2566, 1-10
Nursing, Health, and Public Health Journal
Vol. 2 No. 3, September – December 2023, 1-10

การประยุกต์ใช้พอลิอีเทอร์อีเทอร์คีโตนในงานทันตกรรมประดิษฐ์

The Applications of Polyetheretherketone (PEEK) in Prosthodontics

ไปรยา เศรษฐะทัตต์
Praiya Sresthadatta
แผนกทันตกรรม โรงพยาบาลส่งเสริมสุขภาพ ศูนย์อนามัยที่ 2 พิษณุโลก
Dental Department, Health Promotion Hospital, Regional Health Promotion Center 2, Phitsanulok,
ผู้ให้การติดต่อ (corresponding e -mail): praiya.dent@hotmail.com

(Received: August 19, 2023; Revised: September 14, 2023; Accepted: September 20, 2023)

Abstract

The current trend is moving towards using metal-free restorations and biomaterials that exhibit advanced properties in the complex oral environment. Due to its excellent properties, such as stable chemical properties and biocompatibility, Polyetheretherketone (PEEK) has several applications in dentistry. The study aimed to summarize the experimental and clinical studies conducted about PEEK materials for applications in prosthodontics. Numerous studies have proven that PEEK can be successfully used in prosthodontics. PEEK could be considered a viable alternative material for removable partial dentures, fixed partial dentures, dental implants, and the restoration of maxillofacial defects. However, clinical studies are currently lacking, and further in-vitro and in-vivo studies are still needed to evaluate PEEK as a permanent material.

Keywords: Polyetheretherketone, PEEK, Removable partial denture, Fixed partial denture, Implant

Introduction

In a national community-based survey in Thailand among adults aged 35-44 years, the overall prevalence of partial edentulism was 21.8% in the maxilla, 36.8% in the mandible, and 13.7% in both the maxilla and mandible (Bureau of Dental Health, 2018). Therefore, the need for fixed and removable partial prostheses remains high and will continue to increase (Douglass & Watson, 2002). Advances in dentistry and the development of technologies can be achieved by improving materials. Biocompatibility, low plaque affinity, pleasing aesthetics, and characteristics close to the dental structure are essential to modern materials used in advanced dentistry. They help restore teeth and dentition defects and please demanding patients.

Polyetheretherketone (PEEK) is a polyaryletherketone (PEAK) family member. In 1978, it was developed by a group of English scientists. Later, PEEK was commercialized for industrial applications. By the late 1990s, PEEK became an important high-performance thermoplastic candidate for replacing metal implant components in vertebral surgery as a material of the interbody fusion cage. With the emergence of carbon fiber-reinforced PEEK (CFR-PEEK), this new composite material was exploited for fracture fixation and femoral prosthesis in artificial hip joints (Ma & Tang, 2014).

PEEK is a semi-crystalline linear polycyclic aromatic polymer with excellent mechanical properties, including a low modulus of elasticity (3-4 GPa) closer to that of human bone and dentin. PEEK also has a tensile property comparable to the teeth and considerably low density (1300 kg/m^3), which can result in favorable stress distribution for lightweight framework restorations. In addition, the mechanical properties of PEEK are not altered during sterilization using steam, gamma, and ethylene oxide (Kurtz, 2012; Najeeb et al., 2016). The elastic modulus and tensile strength are summarized in Table 1 (Adem et al., 2022; Najeeb et al., 2016). Furthermore, PEEK withstands thermal stress at high temperatures (melting point 343 $^{\circ}$C) without significant degradation, has low water solubility, and can minimize biocorrosion within body fluid, giving it stable chemical and physical properties (Kurtz, 2012; Liebermann et al., 2016). PEEK is resistant to hydrolysis, non-mutagenic, non-cytotoxic, and non-allergic, making it one of the most biocompatible materials (Katzer et al., 2002; Liebermann et al., 2016; Zoidis et al., 2016). Additionally, PEEK is radiolucent and generates few imaging artifacts (Rauch et al., 2020). PEEK is an essential, high-performance dental material with dental implants, prosthodontics, and orthodontics applications. This literature review aimed to summarize the studies that have been carried out about PEEK applications in prosthodontics (Fig 1).

Table 1. The elastic modulus and tensile strength of pure PEEK, PEEK composites, mineralized human tissues, and dental alloys (Adem et al., 2022; Najeeb et al., 2016).

Material	Elastic modulus (GPa)	Tensile strength (MPa)
Titanium	102-110	954-976
PMMA	3-5	48-76
PEEK	3-4	80
CFR-PEEK	18	120
GFR-PEEK	12	97
Cortical bone	14	104-121
Enamel	40-83	47.5
Dentin	15	104

PMMA: Polymethyl methacrylate, CFR-PEEK: Carbon fiber-reinforced-polyetheretherketone, GFR-PEEK: Glass fiber-reinforced-polyetheretherketone.

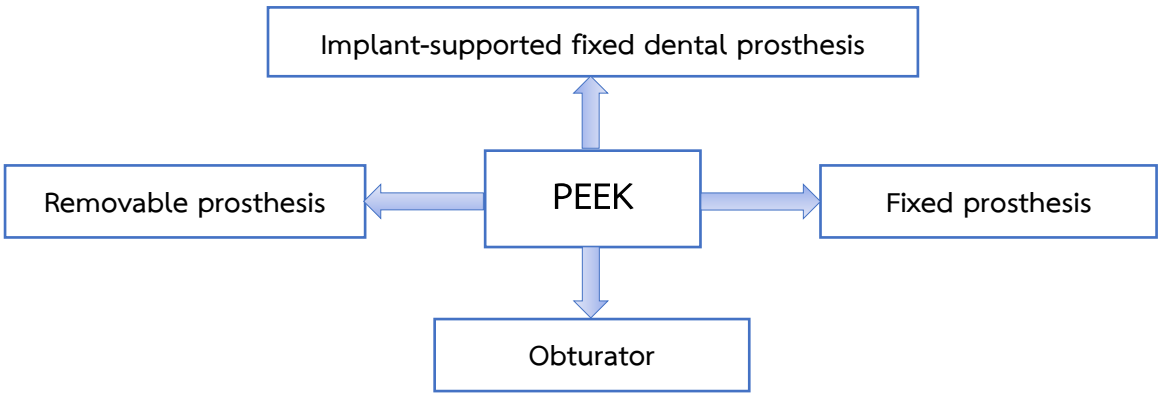

Fig 1. Applications of PEEK in prosthodontics.

PEEK for a removable prosthesis

Removable dental prostheses (RDPs) can be fabricated from PEEK, either injection molding or CAD/CAM systems. Previous clinical report has suggested PEEK frameworks in combination with acrylic resin denture teeth and heat-cured acrylic resin denture bases as an alternative to conventional Cobalt-Chromium (CoCr) frameworks. The study reported high patient satisfaction regarding esthetics, retention, and comfort. Due to its high elasticity, PEEK could reduce the stresses and distal torque on abutment teeth during function (Zoidis et al., 2016). In agreement with this statement, a three-dimensional finite element analysis by Chen et al. (2019) showed that PEEK frameworks caused lower stress values on the periodontal ligament than CoCr and titanium alloy. Therefore, PEEK RDPs could be recommended for patients with poor periodontal conditions. However, the same study found that PEEK caused the highest stresses on the mucosa and the most significant displacement on the free end. The authors concluded that PEEK should be used cautiously in distal extension RDPs. Furthermore, a clinical study demonstrated that PEEK denture frameworks had similar effects on oral health-related quality of life, patient satisfaction, and periodontal outcomes compared to CoCr denture frameworks (Ali et al., 2020).

Retention force and fatigue resistance are crucial factors for removable prosthesis clasps. Tannous et al. (2012) found that PEEK clasps had a lower retaining force than CoCr clasps. Nevertheless, the retention properties of the PEEK clasp remained stable over time. However, the properly designed PEEK clasps with an undercut of 0.5 mm could provide adequate retention for clinical use (Gentz et al., 2022). PEEK can be used as a framework material for complete dentures to reduce the denture deformation responsible for midline fractures (Hada et al., 2020). Overdenture frameworks are also fabricated from PEEK to promote proprioception and cushioning effect on the underlined teeth and supporting structures (Zoidis, 2018b). In an RDP framework made of PEEK, patient comfort is enhanced by its strength and lightweight, absence of metallic taste, lack of thermal and electrical conductivity, scanner and radiographic friendliness, and non-allergic.

PEEK for a fixed prosthesis

PEEK reinforced with organic fillers fabricates provisional and definitive crowns and fixed partial dentures (FPDs). Since PEEK is opaque, it should be veneered with composite resin to achieve an aesthetic. Studies have reported high fracture resistance (Prechtel et al., 2020), high patient comfort and acceptability, and better marginal fit of CAD/CAM PEEK inlays (Rajamani et al., 2021). Modified PEEK for single crown frameworks veneered with composite resin has been suggested for patients with metal allergies and weak abutments for patients with solid masseters or parafunctional habits (Badran et al., 2021). The same composite material has been used to veneer PEEK endocrown frameworks with predictable results (Ghajghouj & Taşar-Faruk, 2019).

Double crown systems, including telescopic crowns with a 0° taper and conus crowns, can provide retention for RDP due to their guidance, support, and protection against dislodging movements (Stock et al., 2016). In the double crown systems, CAD/CAM-manufactured PEEK secondary crowns exhibited sufficient and stable retentive force values, even after artificial aging, equivalent to 10 years of clinical usage (Schubert et al., 2019). Moreover, Luft et al. (2021) recommended using PEEK for secondary crowns when treating patients with few residual abutment

teeth. A previous study reported that titanium/PEEK material combinations exhibited similar retention forces as precious alloy/precious alloy telescopic crowns. In addition, PEEK secondary crowns showed more favorable outcomes regarding wear resistance (Schimmel et al., 2021). Another in vitro study demonstrated that milled PEEK could also be used as primary crown material with high retentive forces in combination with secondary crowns made of zirconia, CoCr, or electroformed (Stock et al., 2016). Recent investigations have already proven the suitability of PEEK as a secondary crown material for retaining implant overdentures, providing a reduction of stresses transmitted to the implants due to the stress-breaking capacity of PEEK and the acceptable initial and final retention values (Emera et al., 2020). A clinical case presented by Siewert (2018) described using primary zirconia copings and secondary PEEK framework veneered with monolithic zirconia to rehabilitate an edentulous patient with titanium intolerance. The study reported high chewing comfort and patient satisfaction with low weight, perfect fit, and retention prosthesis with no signs of soft tissue inflammation.

Rodríguez et al. (2021) examined the potential of PEEK as an alternative FPD material and reported that CoCr (11157 N) had the highest fracture values after thermocycling, followed by PEEK (3132 N) and zirconia (1860 N); all were within the clinically acceptable range. In another study, Stawarczyk et al. (2013) reported a lower fracture value (1383 N) of an uncemented three-unit milled PEEK FPD and noted that deformation appeared to start at 1200 N. Therefore, the PEEK substructure could be suitable for restorations in load-bearing areas. However, a finite element analysis comparing PEEK, zirconia, and metal-ceramic three-unit FDPs found the highest deformation and stress upon bridge body and bone for PEEK FDP (Alqahtani, 2019).

In addition, Tasopoulos et al. (2021) recently published a case report describing a successful restoration of inlay-retained PEEK FPDs over an observation period of 8 years. A pilot clinical study by Raj et al. (2020) demonstrated satisfactory clinical outcomes of PEEK as posterior FPDs. Only 5% of PEEK FPDs failed because of de-bonding, while remaining restorations were maintained without fracture, and 10% showed marginal discoloration, but marginal adaptation exhibited no significant change over one year. The overall conclusion of the previous studies is that PEEK can be used for fixed dental prostheses, although the clinical evidence needs to be improved.

PEEK for an implant-supported fixed dental prosthesis

Frameworks for implant-supported fixed dental prostheses (IFDPs) are typically fabricated by casting metal alloys or milling titanium or zirconia. However, Parmigiani-Izquierdo et al. (2017) used PEEK frameworks veneered with resin composite as implant-supported crowns for patients with metal allergy. PEEK has also been used for framework fabrication for short or long-span all-on-four implant restorations. The cushion effect is a distinct advantage over more complex materials, leading to a lower risk of mechanical complications (Zoidis, 2018a). Consistent with this statement, Wachtel et al. (2019) found a favorable fracture mode for PEEK compared to conventional materials when evaluating screw-retained PEEK crowns on titanium implants, with the bending points shifted coronally, which protected the implant and abutment screws from damage**.** No screw loosening or veneer complications were observed. On the other hand, using rigid metal or zirconia frameworks

could lead to plastic deformation of the implant shoulder (Sailer et al., 2018). Moreover, Mourya et al. (2021) suggested using PEEK restorations in bruxism patients could reduce stress generation in bone and the risk of implant failure.

Finite element analysis helps predict the mechanical behavior of PEEK in IFDPs. Due to its low elastic modulus, PEEK provides a cushioning effect on occlusal forces. When PEEK frameworks are combined with low modulus of elasticity materials such as polymethyl methacrylate or composite resin, occlusal forces on the restoration and opposing dentition are further reduced (Zoidis, 2018a). However, the shock-absorbing capacity of the PEEK prosthetic framework is relatively limited and effective only under compressive stress (Kelkar et al., 2021). In addition, a finite element analysis on different framework materials for implant-supported fixed mandibular prostheses revealed the highest deformation for PEEK and PMMA frameworks, which reduced the von Mises stresses in the frameworks, implants, and abutments. Moreover, PEEK frameworks showed critical tensile stress values in trabecular bone, while zirconia, CoCr, and titanium reached stress values in the bone that were within physiologic limits (Sirandoni et al., 2019).

To ensure good long-term results of implant-supported prostheses, adequate fracture strength is required. An in vitro study showed that an implant-supported three-unit fixed partial denture from PEEK could bear high occlusal forces such as excessive crown height space (Nazari et al., 2016). In addition, Preis et al. (2017) also suggested that PEEK crowns can be applied to bonded or screw-retained restorations. In contrast, a total failure rate was observed in composite paste-veneered PEEK frameworks used for screw-retained repairs, suggesting that the insertion of screw channels weakened the PEEK frameworks. Moreover, zirconia implant-supported frameworks with cantilevers exhibited higher fracture resistance than PEEK-based materials (Yilmaz et al., 2019).

A few studies have demonstrated satisfactory clinical outcomes of PEEK implant-supported full-arch fixed prostheses with a low incidence of biological and mechanical complications (de Araújo Nobre et al., 2020; Wang et al., 2021). PEEK restorations are also considered to benefit patients with temporomandibular joint disorder complications (Wang et al., 2021). Another advantage of PEEK is its radiolucency, which may facilitate the cement removal and the diagnosis of screw loosening (Zoidis, 2018a). These clinical reports and studies have concluded that PEEK superstructures could be a prospective treatment option for IFDPs.

PEEK for an obturator

Another application of PEEK is the construction of a removable obturator. In a clinical report by Costa-Palau et al. (2014), a maxillary obturator was fabricated from PEEK for a patient with an oronasal defect. They found that the PEEK obturator is weightless and biocompatible, with good retention and easy polishing. Aesthetic, retention, and patient comfort were greatly enhanced.

However, no experimental studies on PEEK obturators are available in the literature. Villefort et al. (2020) used a finite element analysis to evaluate the mechanical response of implant-retained obturator prostheses. The authors suggested that PEEK can be used as framework material to reduce the bone strain around the implants and the stress concentration in the bar structure. However, compared to titanium and CoCr alloys, PEEK increases the risk of prosthetic screws loosening and

even fracture. Nevertheless, further studies are needed to elevate the efficacy of PEEK obturators compared with conventional acrylic prostheses.

Conclusion

Several in vitro studies and clinical reports suggested that PEEK could be suitable for fabricated fixed and removable dental prostheses and implant prosthodontics due to its favorable mechanical, chemical, and physical properties. However, further studies are needed to elevate the long-term performance of these prostheses before PEEK can be safely recommended as an alternative to well-establish prosthodontic materials.

Conflict of interest

The authors have no conflicts of interest to report.

References

Adem, N., Bal, B., & Kazazoğlu, E. (2022). Comparative study of chemical and mechanical surface treatment effects on the shear bond strength of polyether-ether-ketone to veneering resin. *International Journal of Prosthodontics, 35*(2), 201–207. https://doi.org/10.11607/ijp.6938

Ali, Z., Baker, S., Sereno, N., & Martin, N. (2020). A pilot randomized controlled crossover trial comparing early ohrqol outcomes of cobalt-chromium versus peek removable partial denture frameworks. *International Journal of Prosthodontics, 33*(4), 386-392. https://doi.org/10.11607/ijp.6604

Alqahtani, W. M. (2019). Selection of fixed dental prosthesis materials based on a finite element study. *International Journal of Medical Dentistry, 23*(4), 547-552. https://chula.idm.oclc.org/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=ddh&AN=141301328&site=eds-live

Badran, A., Zaki, A., & Rabie, K. (2021). One Year clinical evaluation of milled biohpp polyetheretherketone (PEEK)-based versus metal ceramic single crowns (Randomized controlled clinical trial). *Brazilian Dental Science, 24*(3). https://doi.org/10.14295/bds.2021.v24i3.2518

Bureau of Dental Health. (2018). *The 8th National Oral Health Survey 2017 of Thailand.* Nonthaburi: Bureau of Dental Health, Department of Health, Ministry of Public Health; 2018 [cited 2022 May]. https://dental.anamai.moph.go.th/web upload/migrated/files/dental2/n2424_765046ad86a54985537887456d464d2f_surveu_8th_2nd_แยกเขตสุขภาพ.pdf (in Thai)

Chen, X., Mao, B., Zhu, Z., Yu, J., Lu, Y., Zhang, Q., Yue, L., & Yu, H. (2019). A three-dimensional finite element analysis of mechanical function for 4 removable partial denture designs with 3 framework materials: CoCr, Ti-6Al-4V alloy and PEEK. *Scientific Reports, 9*(1), 13975. https://doi.org/10.1038/s41598-019-50363-1

Costa-Palau, S., Torrents-Nicolas, J., Brufau-de Barberà, M., & Cabratosa-Termes, J. (2014). Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: A clinical

report. *Journal of Prosthetic Dentistry, 112*(3), 680-682. https://doi.org/10.1016/j.prosdent.2013.10.026

de Araújo Nobre, M., Moura Guedes, C., Almeida, R., Silva, A., & Sereno, N. (2020). Hybrid polyetheretherketone (PEEK)-Acrylic resin prostheses and the all-on-4 concept: A full-arch implant-supported fixed solution with 3 years of follow-up. *Journal of Clinical Medicine, 9*(7). https://doi.org/10.3390/jcm9072187

Douglass, C. W., & Watson, A. J. (2002). Future needs for fixed and removable partial dentures in the United States. *Journal of Prosthetic Dentistry, 87*(1), 9-14. https://doi.org/10.1067/mpr.2002.121204

Emera, R., Elgamal, M., & Altonbary, G. (2020). Retention force of all-zirconia, all-polyetheretherketone, and zirconia-polyetheretherketone telescopic attachments for implant-retained overdentures: In vitro comparative study. *Journal of Dental Implants, 10*(2), 78-83. https://doi.org/10.4103/jdi.jdi_4_20

Gentz, F. I., Brooks, D. I., Liacouras, P. C., Petrich, A., Hamlin, C. M., Ellert, D. O., & Ye, L. (2022). Retentive forces of removable partial denture clasp assemblies made from polyaryletherketone and Cobalt-Chromium: A comparative study. *Journal of Prosthodontics, 31*(4), 299-304. https://doi.org/10.1111/jopr.13398

Ghajghouj, O., & Taşar-Faruk, S. (2019). Evaluation of fracture resistance and microleakage of endocrowns with different intracoronal depths and restorative materials luted with various resin cements. *Materials, 12*(16). https://doi.org/10.3390/ma12162528

Hada, T., Suzuki, T., Minakuchi, S., & Takahashi, H. (2020). Reduction in maxillary complete denture deformation using framework material made by computer-aided design and manufacturing systems. *Journal of the Mechanical Behavior of Biomedical Materials, 103*, 103514. https://doi.org/https://doi.org/10.1016/j.jmbbm.2019.103514

Katzer, A., Marquardt, H., Westendorf, J., Wening, J. V., & von Foerster, G. (2002). Polyetheretherketone--cytotoxicity and mutagenicity in vitro. *Biomaterials, 23*(8), 1749-1759. https://doi.org/10.1016/s0142-9612(01)00300-3

Kelkar, K. C., Bhat, V., & Hegde, C. (2021). Finite element analysis of the effect of framework materials at the bone-implant interface in the all-on-four implant system. *Dental Research Journal, 18*, 1-1. https://pubmed.ncbi.nlm.nih.gov/34084288

Kurtz, S. M. (2012). Chapter 1 - An overview of PEEK biomaterials. In S. M. Kurtz (Ed.), *PEEK Biomaterials Handbook* (pp. 1-7). William Andrew Publishing. https://doi.org/https://doi.org/10.1016/B978-1-4377-4463-7.10001-6

Liebermann, A., Wimmer, T., Schmidlin, P. R., Scherer, H., Löffler, P., Roos, M., & Stawarczyk, B. (2016). Physicomechanical characterization of polyetheretherketone and current esthetic dental CAD/CAM polymers after aging in different storage media. *Journal of Prosthetic Dentistry, 115*(3), 321-328.e322. https://doi.org/10.1016/j.prosdent.2015.09.004

Luft, V., Pospiech, P., Schurig, A., & Schmitter, M. (2021). In vitro investigations on retention force behavior of conventional and modern double crown systems. *Dental Materials Journal, 37*(1), 191-200. https://doi.org/10.1016/j.dental.2020.10.028

Ma, R., & Tang, T. (2014). Current strategies to improve the bioactivity of PEEK. *International Journal of Molecular Sciences, 15*(4), 5426-5445. https://doi.org/10.3390/ijms15045426

Mourya, A., Nahar, R., Mishra, S. K., & Chowdhary, R. (2021). Stress distribution around different abutments on titanium and CFR-PEEK implant with different prosthetic crowns under parafunctional loading: A 3D FEA study. *Journal of Oral Biology and Craniofacial Research, 11*(2), 313-320. https://doi.org/10.1016/j.jobcr.2021.03.005

Najeeb, S., Zafar, M. S., Khurshid, Z., & Siddiqui, F. (2016). Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. *Journal of Prosthodontics Research, 60*(1), 12-19. https://doi.org/10.1016/j.jpor.2015.10.001

Nazari, V., Ghodsi, S., Alikhasi, M., Sahebi, M., & Shamshiri, A. R. (2016). Fracture strength of three-unit implant supported fixed partial dentures with excessive crown height fabricated from different materials. *Journal of Dentistry (Tehran), 13*(6), 400-406.

Parmigiani-Izquierdo, J. M., Cabaña-Muñoz, M. E., Merino, J. J., & Sánchez-Pérez, A. (2017). Zirconia implants and peek restorations for the replacement of upper molars. *International Journal of Implant Dentistry, 3*(1), 5. https://doi.org/10.1186/s40729-016-0062-2

Prechtel, A., Stawarczyk, B., Hickel, R., Edelhoff, D., & Reymus, M. (2020). Fracture load of 3D printed PEEK inlays compared with milled ones, direct resin composite fillings, and sound teeth. *Clinical Oral Investigations, 24*(10), 3457-3466. https://doi.org/10.1007/s00784-020-03216-5

Preis, V., Hahnel, S., Behr, M., Bein, L., & Rosentritt, M. (2017). In-vitro fatigue and fracture testing of CAD/CAM-materials in implant-supported molar crowns. *Dental Materials Journal, 33*(4), 427-433. https://doi.org/10.1016/j.dental.2017.01.003

Raj, D. A., Chander, N. G., Reddy, J. R., & Balasubramaniam, M. (2020). Clinical acceptability of PEEK fixed dental prosthesis in partially edentulous patient - A one year single arm pilot study. *Journal of Oral Biology and Craniofacial Research, 10*(4), 523-528. https://doi.org/10.1016/j.jobcr.2020.08.006

Rajamani, V. K., Reyal, S. S., Gowda, E. M., & Shashidhar, M. P. (2021). Comparative prospective clinical evaluation of computer aided design/ computer aided manufacturing milled BioHPP PEEK inlays and Zirconia inlays. *Journal of Indian Prosthodontic Society, 21*(3), 240-248. https://doi.org/10.4103/jips.jips_57_21

Rauch, A., Hahnel, S., Günther, E., Bidmon, W., & Schierz, O. (2020). Tooth-Colored CAD/CAM materials for application in 3-unit fixed dental prostheses in the molar area: An illustrated clinical comparison. *Materials (Basel), 13*(24). https://doi.org/10.3390/ma13245588

Rodríguez, V., Tobar, C., López-Suárez, C., Peláez, J., & Suárez, M. J. (2021). Fracture load of metal, zirconia and polyetheretherketone posterior CAD-CAM milled fixed partial denture frameworks. *Materials (Basel), 14*(4). https://doi.org/10.3390/ma14040959

Sailer, I., Asgeirsson, A. G., Thoma, D. S., Fehmer, V., Aspelund, T., Özcan, M., & Pjetursson, B. E. (2018). Fracture strength of zirconia implant abutments on narrow diameter implants with internal and external implant abutment connections: A study on the titanium resin base concept. *Clinical Oral Implants Research, 29*(4), 411-423. https://doi.org/10.1111/clr.13139

Schimmel, M., Walther, M., Al-Haj Husain, N., Igarashi, K., Wittneben, J., & Abou-Ayash, S. (2021). Retention forces between primary and secondary CAD/CAM manufactured telescopic crowns: an in vitro comparison of common material combinations. *Clinical Oral Investigations, 25*(11), 6297-6307. https://doi.org/10.1007/s00784-021-03928-2

Schubert, O., Reitmaier, J., Schweiger, J., Erdelt, K., & Güth, J. F. (2019). Retentive force of PEEK secondary crowns on zirconia primary crowns over time. *Clinical Oral Investigations, 23*(5), 2331-2338. https://doi.org/10.1007/s00784-018-2657-x

Siewert, B. (2018). Metal-free implant-supported restorations in the edentulous jaw. *EDI Journal, 3*, 68-74.

Sirandoni, D., Leal, E., Weber, B., Noritomi, P. Y., Fuentes, R., & Borie, E. (2019). Effect of different framework materials in implant-supported fixed mandibular prostheses: A finite element analysis. *International Journal of Oral & Maxillofacial Implants, 34*(6), e107-e114. https://doi.org/10.11607/jomi.7255

Stawarczyk, B., Beuer, F., Wimmer, T., Jahn, D., Sener, B., Roos, M., & Schmidlin, P. R. (2013). Polyetheretherketone-a suitable material for fixed dental prostheses? *Journal of Biomedical Materials Research - Part B Applied Biomaterials, 101*(7), 1209-1216. https://doi.org/10.1002/jbm.b.32932

Stock, V., Schmidlin, P. R., Merk, S., Wagner, C., Roos, M., Eichberger, M., & Stawarczyk, B. (2016). PEEK Primary Crowns with Cobalt-Chromium, Zirconia and Galvanic Secondary Crowns with Different Tapers-A Comparison of Retention Forces. *Materials (Basel), 9*(3). https://doi.org/10.3390/ma9030187

Tannous, F., Steiner, M., Shahin, R., & Kern, M. (2012). Retentive forces and fatigue resistance of thermoplastic resin clasps. *Dental Materials Journal, 28*(3), 273-278. https://doi.org/10.1016/j.dental.2011.10.016

Tasopoulos, T., Pachiou, A., Kouveliotis, G., Karaiskou, G., Ottenga, M., & Zoidis, P. (2021). An 8-year clinical outcome of posterior inlay retained resin bonded fixed dental prosthesis utilizing high performance polymer materials: A clinical report. *Journal of Prosthodontics, 30*(1), 19-23. https://doi.org/10.1111/jopr.13266

Villefort, R. F., Tribst, J. P. M., Dal Piva, A. M. O., Borges, A. L., Binda, N. C., Ferreira, C. E. A., Bottino, M. A., & von Zeidler, S. L. V. (2020). Stress distribution on different bar materials in implant-retained palatal obturator. *PLoS One, 15*(10), e0241589. https://doi.org/10.1371/journal.pone.0241589

Wachtel, A., Zimmermann, T., Sütel, M., Adali, U., Abou-Emara, M., Müller, W. D., Mühlemann, S., & Schwitalla, A. D. (2019). Bacterial leakage and bending moments of screw-retained, composite-veneered PEEK implant crowns. *Journal of the Mechanical Behavior of Biomedical Materials, 91*, 32-37. https://doi.org/10.1016/j.jmbbm.2018.11.027

Wang, J., Wu, P., Liu, H. L., Zhang, L., Liu, L. P., Ma, C. F., & Chen, J. H. (2021). Polyetheretherketone versus titanium CAD-CAM framework for implant-supported fixed complete dentures: A retrospective study with up to 5-year follow-up. *Journal of Prosthodontics Research*. https://doi.org/10.2186/jpr.JPR_D_20_00142

Yilmaz, B., Batak, B., & Seghi, R. R. (2019). Failure analysis of high performance polymers and new generation cubic zirconia used for implant-supported fixed, cantilevered prostheses. *Clinical Implant Dentistry and Related Research, 21*(6), 1132-1139. https://doi.org/10.1111/cid.12844

Zoidis, P. (2018a). The all-on-4 modified polyetheretherketone treatment approach: A clinical report. *Journal of Prosthetic Dentistry, 119*(4), 516-521. https://doi.org/10.1016/j.prosdent.2017.04.020

Zoidis, P. (2018b). Polyetheretherketone overlay prosthesis over high noble ball attachments to overcome base metal sensitivity: A clinical report. *Journal of Prosthodontics, 27*(8), 688-693. https://doi.org/10.1111/jopr.12747

Zoidis, P., Papathanasiou, I., & Polyzois, G. (2016). The use of a modified Poly-Ether-Ether-Ketone (PEEK) as an alternative framework material for removable dental prostheses. A clinical report. *Journal of Prosthodontics, 25*(7), 580-584. https://doi.org/10.1111/jopr.12325