Polyetheretherketone versus titanium CAD-CAM framework for implant-supported fixed complete dentures: a retrospective study with up to 5-year follow-up

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Abstract
Purpose: To evaluate the performance of polyetheretherketone (PEEK) versus titanium computer-aided designed and manufactured (CAD-CAM) framework for implant-supported fixed complete dentures (ISFCDs) with a follow-up for a duration of up to 5 years.
Methods: Consecutively edentulous patients who underwent ISFCDs with a PEEK framework or titanium framework at one dental specialist center were included in this retrospective study. Implant/prosthesis survival rates, mechanical/biological complications, and bone and soft tissue parameters were analyzed. Overall survival was analyzed using Kaplan-Meier survival curves and the log-rank test.
Results: Sixty ISFCDs (29 PEEK, 31 titanium) performed on 43 edentulous patients (331 implants) were included. An implant survival rate of 100% was obtained. There was no significant difference in the cumulative prosthesis survival rate between the PEEK (93.1%) and titanium groups (93.5%). The most common mechanical complications were fracture of the artificial veneer in both the PEEK (13.8%) and titanium (16.7%) groups. Bruxers had a higher prevalence of mechanical complications than non-bruxers (p<0.05). The biological complications included bleeding upon probing (13.8% for the PEEK group; 16.1% for the titanium group), soft tissue inflammation (3.4% for the PEEK group; 3.2% for the titanium group), and temporomandibular disorders (6.5% for the titanium group). The vertical bone loss was significantly lower in the PEEK group (0.70 mm) than in the titanium group (0.96 mm). Smokers had a significantly higher prevalence of biological complications than non-smokers.
Conclusions: Within the limitations of this study, ISFCDs with PEEK frameworks can provide good prognosis for edentulous patients, still requiring longer-term validation.
Keywords: Polyetheretherketone (PEEK), Titanium, Frameworks, Implant-supported fixed complete dentures

1. Introduction
Implant-supported fixed complete dentures (ISFCDs) with immediate function protocols have increasingly been recognized as predictable treatments for edentulous patients, providing the restoration of aesthetics and mastication[1]. Immediate function protocols involve the insertion of implants avoiding bone augmentation procedures, the insertion of interim ISFCDs within 7 days after implant surgery, and rehabilitation by definitive ISFCDs 6 months later[1,2]. As a key factor for the long-term success of these standard protocols, implant frameworks can hold the implants together to support and connect the implant/abutment to the veneering materials. Thus, implant frameworks should have good biocompatibility, excellent physical and mechanical properties, an accurate fit to both implants and abutments, and compatibility with aesthetic veneering materials.

Titanium and zirconia, which provide high biocompatibility, corrosion resistance, and excellent machining performance for CAD-CAM, are commonly used for implant frameworks[3,4]. Nevertheless, the high stiffness measured by the flexural strength (titanium: 434 MPa;
zirconia: 900–1,100 MPa) and elastic modulus (titanium: 115,000 MPa; zirconia: 205,000 MPa) of these frameworks can be considered as potential disadvantages for the conduction of occlusal loading, especially in ISFCDs[5,6]. The tensile and compressive forces are greatly increased around the implants when connected to these rigid frameworks. The stress concentration of the rigid connection is a common risk factor for peri-implant bone loss and implant/prosthesis failure. Therefore, a new framework material with low elastic modulus for relieving stress concentration is promising.

Polyetheretherketone (PEEK) is a high-performance polymer belonging to the polyaryletherketone group, and possesses excellent physical and chemical properties such as low specific weight (1.3 g/cm³), low flexural strength (165 – 170 MPa), suitable elasticity (3,600 MPa), and suitable hardness (20 HV)[7,8]. Following the confirmation of its biocompatibility and mechanical behavior, PEEK has been widely employed as a biomaterial in orthopedic fields for many decades. The main beneficial feature of this material is that its elastic modulus is lower than that of metallic materials and is relatively similar to that of human bone, thus allowing it to reduce the stress on the surrounding bone. Owing to its unique white color and mechanical properties, PEEK has been increasingly applied for fixed and removable prostheses[9], especially for implant CAD-CAM frameworks[10]. It has been demonstrated that PEEK can function as a stress breaker to minimize the forces transmitted to the bone-implant interface[11]. Some clinical reports have suggested the use of PEEK as a framework material for ISFCDs[11,12]. Maló et al.[13] conducted a short-term prospective cohort study to assess the clinical outcomes of full-arch implant-supported fixed hybrid PEEK-acrylic resin prostheses. These clinical reports and studies suggest that ISFCDs with a PEEK framework are an attractive alternative to the traditional complete-arch implant-supported fixed hybrid titanium prosthesions owing to their superior mechanical properties. However, studies evaluating the predictability of this material in ISFCDs are limited, especially those with long-term follow-up.

The aim of this study was to retrospectively assess the clinical outcomes of edentulous patients receiving ISFCDs with PEEK CAD-CAM frameworks and polymethylmethacrylate (PMMA) veneers. Furthermore, the survival rates and complications of PEEK frameworks in ISFCDS were evaluated and compared to those of titanium frameworks with up to 5 years of follow-up.

2. Materials and Methods

2.1. Subject

From March 2015 to December 2018, consecutively edentulous patients who underwent ISFCDs with PEEK-PMMA veneer prostheses or titanium-PMMA veneer prostheses at a dental specialist center (Jinan Military General Hospital, Jinan, China) were included. The study was approved by the ethical committee of the Jinan Military General Hospital (registration number: JMGH2017018), and informed consent was obtained from all participants.

2.2. Inclusion and exclusion criteria

Consecutive patients who underwent ISFCDs with PEEK-PMMA veneer prostheses or titanium-PMMA veneer prostheses, available for regular follow-ups, were included. Patients were excluded if they did not have at least six months of follow-up after installation of the prosthesis.

2.3. Definitions

The patients were divided into two groups (PEEK and titanium groups) based on the framework materials of the dental records. The PEEK group included patients who underwent ISFCDs with individual PMMA veneers cemented onto a CAD-CAM PEEK framework, while the titanium group involved patients who underwent ISFCDs with individual PMMA veneers cemented onto a CAD-CAM titanium framework.

Implant survival was evaluated using the modified criteria: the implant remaining in situ and supporting a functional prosthesis during the entire observation time[14]. Prosthesis survival was considered as remaining functional and did not need to be substituted[4]. The time in situ of the prostheses was calculated from the time of prosthesis installation to the last clinical examination.

Patients were considered to have bruxism based on self-report of clenching/grinding during sleep or during wakefulness, along with the inspection part of a clinical examination[15,16]. Smoking was also based on self-report, using questionnaires following the same guidelines used in a recent study[2]. Patients who smoked a minimum of 1 cigarette per day were classified as smokers.

Mechanical complications: loss/fraction of acrylic resin veneers; fracture/microcrack of the prosthesis framework; fracture of prosthetic/abutment screws; fracture of implant; fracture of prosthetic abutment; prosthetic/abutment screw loosening or loss.

Biological complications: bleeding upon probing; mucosal swelling; implant failure; temporomandibular disorders (TMD). In addition, some other parameters related to the peri-implant biological situation, such as vertical bone loss, peri-implant pocket depth, and plaque index, were evaluated[14,17].

In the present study, inter-rater reliability is enhanced by training data collectors, providing them with a guide for recording their observations, monitoring the quality of the data collection over time to see that people are not burning out, and offering a chance to discuss difficult issues or problems.

2.4. Surgery protocol

Surgery was performed under local anesthesia. A crestal incision was performed and extended bilaterally from the second molar region, while a vestibular releasing incision was made at the middle of the anterior teeth region. A full-thickness flap was elevated, and the standard procedure for implant insertion (copaSKY, Bredent GmbH & Co. KG, Senden, Germany) was implemented to guarantee a final torque of over 35 Newtons/cenimeter (N · cm)[18].

2.5. Interim ISFCDS protocol

All patients were rehabilitated by interim ISFCDs on the same day after implant surgery[12]. Impressions were constructed immediately after implant surgery. The interim ISFCDs were produced by individual artificial teeth (Neo. lign, Bredent GmbH & Co. KG, Senden, Germany) and heat-polymerized acrylic resin (Trelvalon, Dentsply Sirona, York, USA) with a reinforced steel wire. After checking the passive fit of the prostheses with imaging and clinical examination, a torque of 18 N · cm was applied to the prosthetic screws.
2.6. Definitive ISFCDs protocol

Definitive ISFCDs were performed 6 months later. A definitive impression was constructed by adding reaction silicone impression materials (Virtual Heavy/Light Body; Ivoclar VivaDent AG, Schaan, Principality of Liechtenstein). A facebow transfer and centric interocclusal record were carried out using interim prostheses. The casts were mounted on a semi-adjustable articulator (Artex-type CT; Amann Girrbach Co., Koblach, Austria). The dental laboratory cemented 12-14 individual PMMA composite veneers (Novo lign; Bredent GmbH & Co. KG, Senden, Germany) onto a titanium framework with pink acrylic resin (Crea. lign; Bredent GmbH & Co. KG, Senden, Germany), thus replicating the missing gingival tissues in the titanium group. In the PEEK group, the changes were mainly attributed to the framework material (breCAM. BioHPP disk; Bredent GmbH & Co. KG, Senden, Germany)[12].

The laboratory protocol had the following characteristics: A full-contour mock-up of the definitive prosthesis was made with definitive PMMA composite veneers (Novo. lign; Bredent GmbH & Co. KG, Senden, Germany), and low-contraction autopolymerizing acrylic resin (Pi-Ku-Plast; Bredent GmbH & Co. KG, Senden, Germany). After the full-contour mock-up was transferred intraorally to verify the aesthetic and occlusal effects, definitive prostheses were manufactured. The acrylic–resin interim framework was designed following the cutback procedure. The acrylic resin interim framework for the PEEK group needs to be of more thickness buccally/lingually, and vertically (at least 5 mm), special retentive elements for veneer materials should be designed as integral parts, and a calix shape was applied to ensure adequate support and uniform thickness of occlusal material. The acrylic resin interim framework was scanned and transferred using system-specific software (D2000 3D Scanner; 3Shape A/S; Copenhagen, Denmark). The digital data were transferred to a milling machine (308 B; Willemin-Macodel, Delemont, Switzerland) for the fabrication of titanium frameworks, and MCK5 (D3608; Sirona Dental Systems GmbH, Bensheim, Germany) for the fabrication of PEEK frameworks[19]. (Fig.1)

The definitive PMMA composite veneers were cemented to the frameworks according to the silicone index following the adhesive procedure. PMMA composite veneers to titanium frameworks: (1) conditioning of titanium framework: the titanium framework was abraded with airborne-particle (110-μm aluminum oxide at a pressure of 0.3-0.4 MPa), then wet with the primer (MKZ Primer; Bredent GmbH & Co. KG, Senden, Germany) by applying a thin layer of opaquer (Opaquer combo.lign; Bredent GmbH & Co. KG, Senden, Germany), and subsequently polymerized in the light-polymerization unit. (2) Conditioning of the PMMA veneer: the veneer was abraded with airborne particles (110-μm aluminum oxide at a pressure of 0.2-0.3 bar), wet with the primer (visio.link; Bredent GmbH & Co. KG, Senden, Germany), and subsequently hardened in the light polymerization unit. (3) A resin luting agent was used to cement the veneer to the metal framework: Selected tooth shade of the resin luting agent (combo.lign; Bredent GmbH & Co. KG, Senden, Germany) and the veneer fixed on the metal framework using a resin luting agent (combo.lign; Bredent GmbH & Co. KG, Senden, Germany), excess material was removed, and the veneer subsequently polymerized using a light-curing unit[12].

The screw access opening was left open, and a pink shade indirect light-polymerized nanofilled composite resin (crea.lign GUM; Bredent GmbH & Co. KG, Senden, Germany) was polymerized around the veneers and in the pontic gingival area of the prostheses. (Fig.2) Standard polishing (toolkit; Bredent GmbH & Co. KG, Senden, Germany) was performed to ensure shade stability and plaque resistance, and its quality and durability were similar to those of ceramic materials. (Fig.3) After checking the passive fit of the prostheses, an insertion torque of 18 N·cm was placed onto the prosthetic screws. The occlusion was adjusted using articulating papers, as described previously[20]. (Fig. 4)

2.7. Statistical analysis

Statistical analyses were conducted using SPSS version 18.0. The mean, standard deviation (SD), and percentages were calculated for several variables. A paired Student’s t-test was applied for the two independent groups, with continuous variables between the titanium and PEEK groups. A life table was performed for prosthesis survival. Overall survival was analyzed using Kaplan–Meier survival curves and compared with the log-rank test. The significance level was set at p < 0.05.
3. Results

A total of 43 edentulous patients (18 women, 25 men) with a mean age of 59.8 years (range: 43–78 years) who underwent 60 immediate ISFCDs (31 in the upper jaws and 29 in the lower jaws) were included. All patients were followed up between 12 months and 57 months, with a mean follow-up period of 26.5 months.

Overall, 331 immediately loaded implants with 46 tilted implants were positioned on the upper and lower jaws, with a survival rate of 100%. All prostheses were found to be structurally intact, but serious mechanical complications leading to prosthesis replacements occurred in 4/60 restorations, scoring a cumulative prosthesis survival rate of 93%. Based on the results of Kaplan-Meier analysis, an overall estimate of the survival time was 53.8 months (95% CI: 50.8 - 56.8 months). The gender distribution and mean age of the patients and the jaw distribution of the implants/restorations are summarized in Table 1. Table 2 shows a comparison between the different groups in the prevalence of bruxers and smokers, and follow-up time between the different factors. The titanium group included 22 patients with a mean age of 61.0 years (range: 43-78 years). Thirty-one prostheses were fabricated for the titanium group with a mean follow-up period of 26.50 months. The titanium group had a 93.5% success rate at the 5-year follow-up (Kaplan-Meier). The overall estimate of the survival time was 52.1 months (95% CI: 48.3 - 56.0 months). The PEEK group included 21 patients with a mean age of 58.6 years (range: 44-74 years). Twenty-nine prostheses were fabricated for the PEEK group with a mean follow-up period of 26.48 months. The PEEK group showed a 93.1% survival rate at the 5-year follow-up (Kaplan-Meier). The overall estimated survival time was 53.7 months (95% CI: 49.3 - 58.1 months). (Fig.5 and Tables 3-4)

Table 5 shows the prevalence of complications according to prosthesis material, jaw, sex, bruxism, and smoking. In the titanium group, mechanical complications occurred in seven prostheses, including veneer fracture and screw loosening. Five prostheses in this group were found to have a veneer fracture. Two patients presented with screw loosening. In the PEEK group, mechanical complications occurred in five prostheses, including veneer fracture and framework microcracks. Notably, framework microcracks were detected in one prosthesis, while the remaining four prostheses were found to have veneer fractures. Bruxers also presented a higher prevalence of mechanical complications than non-bruxers (p<0.05, log-rank test). According to the Cox proportional hazard models (Table 6), mechanical complications presented a higher risk of occurrence in bruxers than in non-bruxers (HR 5.24, p<0.05). The veneer fracture of acrylic teeth also presented a higher risk of occurrence when the ISFCDs were opposed to natural dentition or fixed prostheses. Among the nine prostheses with veneer fractures, the opposing dentition was a fixed implant-supported prosthesis (7 patients) and natural dentition (2 patients). The acrylic resin veneer fracture was solved by repairing in oral, adjusting patients’ occlusions and manufacturing occlusal night-guards. Screw loosening was solved by torque-controlled re-tightening of the prosthetic screws.
Biological complications are also shown in Table 5. In the PEEK group, the main biological complications were found in 5 patients, including bleeding upon probing (4 patients, 16% in 2 patients, 25% in 2 patients) and soft tissue inflammation (1 patient). Meanwhile, for the titanium group, the major biological complications were noted among 8 patients, such as bleeding upon probing (5 patients), soft tissue inflammation (1 patient), and TMD (2 patients). No implant loss or mucosal swelling was observed in any group. Smokers had a significantly higher prevalence of biological complications than non-smokers ($p<0.05$, log-rank test). According to the Cox proportional hazard models (Table 6), biological complications presented a higher risk of occurrence in smokers than in non-smokers (HR 9.34, $p<0.05$). Furthermore, the amount of vertical bone loss was noticeably higher in the titanium group (0.96 mm) than in the PEEK group (0.70 mm) ($p<0.05$). Deeper peri-implant pockets were observed in the titanium group (3.59 mm) than in the PEEK group (2.94 mm) ($p<0.05$). However, no significant differences in bleeding upon probing and plaque index were observed between the two groups. The peri-implant pockets were addressed by non-surgical treatment (mechanical debridement and pocket irrigation with a chlorhexidine gel). Two patients who complained of temporo-mandibular joint (TMJ) pain were treated with an occlusal pad and physical therapy. No functional, aesthetic, or comfort complications were recorded during the follow-up period.

### 4. Discussion

Few long-term follow-up studies and standard protocols are available for the novel framework material PEEK for ISFCDs. The aim of this retrospective clinical study was to assess and compare the performance of PEEK and titanium CAD-CAM frameworks for ISFCDs with up to a 5-year follow-up. Our results showed that a total of 331 immediately loaded implants with 46 tilted implants were positioned on the upper and lower jaws, with a survival rate of 100%. Previous long- and short-term studies of ISFCDs have demonstrated the implant survival rates of 92.7-100%[21–23]. The prosthesis survival rate of PEEK (93.1%) groups in the present study is comparable to that of titanium (93.5%) and other types of ISFCDs[1,24–29]. Dawson et al.[12] employed PEEK for complete fixed and removable dental prostheses. Zoidis[11] fabricated PMMA veneers onto a PEEK implant framework for the treatment of all-on-4 patients. Malo et al.[13] assessed the short-term outcomes of fixed full-arch implant-supported hybrid PEEK-acrylic resin prostheses in all-on-4 patients with a prosthesis survival rate of 98%. Altogether, these clinical reports and studies have concluded that the combination of PEEK frameworks with PMMA veneers can be a prospective treatment option for edentulous patients.

Veneer fracture is one of the most common complications of ISFCDs. It can be influenced by many factors, such as framework design, occlusal veneer materials, framework/veneer bonding strength, occlusal overload, and opposing dentition[30,31]. Bruno reported the prevalence of veneer fracture (Gold/acrylic 29.9%, CoCr/acrylic 25.6%, titanium/acrylic 38.3%, gold/ceramic 36.4%, CoCr/ceramic 8.3%, titanium/acrylic 33.3%) according to prosthesis material in a
10-year follow-up retrospective evaluation of ISCFDs. In the present study, the most common mechanical complications were fracture of the artificial veneer in both the PEEK (13.8%) and titanium (16.7%) groups.

The occurrence of veneer fractures has highlighted the bonding strength between the framework and veneer. The specific chemical composition and low surface energy of PEEK and titanium may hinder their bonding to resin-based materials[32,33]. In the present study, different separate “primed” acrylic resins were required to significantly increase the bonding strength between the PMMA veneers and the frameworks. The primer (visio.link) used in the PEEK framework is a light-curing primer for veneers based on PMMA and PEEK.

The product contains methyl methacrylate and 2-propenoic acid reaction products with pentaerythritol and diphenyl (2,4,6-trimethylphenyl) phosphine oxide[34]. The MKZ primer used in the titanium framework is a bonding agent for bonding metal and resin. The product contains a mixture of butanone (Methylethylketon, MEK, C4H8O) with non-hazardous additions[35]. The resin luting agent (Combo.lign, Bredent GmbH & Co. KG, Senden, Germany) to cement the veneer into the framework contains 7,7,9( or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxo-5,12-dioxadecane-1,16-diyl bis-methacrylate tetramethylene[34]. Stawarczyk et al.[32] also reported that a sufficient tensile bonding strength of veneering resin to PEEK can only be achieved with the addition of adhesive materials (visio.link or Signum PEEK Bond). To strengthen the adhesive characteristics of

| Table 3. Estimated fractions for survival using the Kaplan-Meier product limit estimator for the prostheses in the PEEK group. |
|---------------------------------|---------------------------------|--------------------------------|---------------------------------|
| Time (months) | Status (0= non failure; 1=failure) | Cumulative proportion surviving at the time | No. of cumulative events |
|----------------|---------------------------------|---------------------------------|---------------------------------|
| 0              | 0                               | -                               | 0                               |
| 7              | 1                               | 0.966                           | 0.034                           |
| 11             | 1                               | 0.928                           | 0.049                           |
| 12             | 0                               | -                               | 2                               |
| 18             | 0                               | -                               | 2                               |
| 24             | 0                               | -                               | 2                               |
| 30             | 0                               | -                               | 2                               |
| 36             | 0                               | -                               | 2                               |
| 42             | 0                               | -                               | 2                               |
| 48             | 0                               | -                               | 2                               |
| 54             | 0                               | -                               | 2                               |
| 57             | 0                               | -                               | 2                               |

| Table 4. Estimated fractions for survival using the Kaplan-Meier product limit estimator for the prostheses in the titanium group. |
|---------------------------------|---------------------------------|--------------------------------|---------------------------------|
| Time (months) | Status (0= non failure; 1=failure) | Cumulative proportion surviving at the time | No. of cumulative events |
|----------------|---------------------------------|---------------------------------|---------------------------------|
| 0              | 0                               | -                               | 0                               |
| 10             | 1                               | 0.967                           | 0.033                           |
| 12             | 0                               | -                               | 1                               |
| 18             | 0                               | -                               | 1                               |
| 24             | 0                               | -                               | 2                               |
| 30             | 0                               | -                               | 2                               |
| 36             | 0                               | -                               | 2                               |
| 42             | 0                               | -                               | 2                               |
| 48             | 0                               | -                               | 2                               |
| 54             | 0                               | -                               | 2                               |
| 57             | 0                               | -                               | 0                               |

| Table 5. Prevalence of complications, according to prosthesis material, jaw, sex, bruxism, and smoke. The statistical unit is the implant-supported full-arch fixed dental prosthesis, not the patient nor the implant. |
|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| Group | Loss/fracture of acrylic resin veneers (%) | Fracture/crack of the prosthesis framework (%) | Prosthetic/abutment screws loosing/loss |
|-------|---------------------------------|--------------------------------|--------------------------------|
| Material | Titanium | Maxilla | Mandible |
| PEEK   | 29/32 (10.3) | 29/32 (4.3) | 29/32 (4.3) |
| Titanium | 5/31 (16.1) | 0/31 (0) | 0/31 (0) |
| Jaw | 3/32 (9.4) | 2/32 (6.3) | 1/32 (3.1) |
| Maxilla | 0/31 (0) | 0/31 (0) | 0/31 (0) |
| Mandible | 5/28 (17.9) | 0/28 (0) | 0/28 (0) |
| Sex | 4/35 (11.4) | 0/35 (0) | 1/35 (2.9) |
| Male | 1/35 (2.9) | 0/35 (0) | 0/35 (0) |
| Female | 4/25 (16.0) | 1/25 (4.0) | 1/25 (4.0) |
| Bruxer | 3/47 (6.4) | 0/47 (0) | 1/47 (2.1) |
| No | 0/47 (0) | 0/47 (0) | 1/47 (2.1) |
| Yes | 5/13 (38.5) | 1/13 (7.7) | 1/13 (7.7) |
| Smoker | 7/49 (14.3) | 1/49 (2.0) | 2/49 (4.1) |
| No | 0/49 (0) | 0/49 (0) | 0/49 (0) |
| Yes | 1/11 (9.1) | 0/11 (0) | 0/11 (0) |
| Opposing dentition status | 7/51 (13.7) | 1/51 (2.0) | 1/51 (2.0) |
| Natural/FPD/ISFCD | 0/4 (0) | 0/4 (0) | 0/4 (0) |
| Partially dentate with or without RPD | 1/4 (25) | 0/4 (0) | 0/4 (0) |
| Denture/overdenture | 0/4 (0) | 0/4 (0) | 0/4 (0) |

*p < 0.05 compared with the Titanium group; **p < 0.05 compared with the non-bruxer; *, #, $ p < 0.05 compared with the non-smoker.
PEEK, both physical (e.g., ion beam, ultraviolet light, plasma, etc.) and chemical techniques (e.g., combination of airborne particle abrasion and piranha solution etching) have been exploited. However, these methods often require large instruments and have significant space requirements, which make them impractical for most clinical practices[36]. Therefore, more investigations are needed to develop an appropriate surface treatment method that is more convenient and safer to improve the bonding strength between PEEK and resin-based materials without using strong acids.

Framework design is tremendously important for implant/prosthesis survival rates and the bonding strength between PEEK and veneers. There are some guidelines for designing a PEEK framework in the present study. First, PEEK frameworks need to be of greater thickness, buccally/lingually, and vertically. Then, special retentive elements for veneer materials should be designed as integral parts of the occlusal material. Maló et al.[13] reported that the incidence of veneer adhesion resulting from PEEK infrastructure was 14.3% in a short-term ongoing prospective cohort study. The framework design in that study used an “I” shape, with 5 mm for an occlusocervical height, 4 mm for anterior buccolingual width, and 6 mm for the increased buccolingual width. Further studies should focus on the relationship between the design of PEEK frameworks and bonding strength.

Occlusal veneer materials affect the transmission of occlusal forces and the maintenance of occlusal contacts. The veneer material (novolign) used in our study consists of a high-impact polymer composite filled with microceramic, which can be used for the permanent veneering of metal, ceramic, and polymer frameworks. Owing to their high flexural strength (140 MPa) and low modulus of elasticity (approximately 3,000 MPa), veneers may have a shock-absorbing effect for implant prostheses[37].

Table 6. Comparison between mechanical complication vs non-mechanical complication and biological complications vs non-biological complication IS-FCDs according to different factors, and univariate Cox proportional hazard models.

| Factor                          | Mechanical complication | Hazard ratio | P value | Biological complications (%) | Hazard ratio | P value |
|---------------------------------|-------------------------|--------------|---------|------------------------------|--------------|---------|
| Material                        |                         |              |         |                              |              |         |
| PEEK                            | 4/29 (13.8)             | 1            | 0.236   | 6/29 (20.7)                  | 1            | 0.373   |
| Titanium                        | 7/31 (22.6)             | 1.404        |         | 9/31 (29)                   | 0.793        |         |
| Jaw                             |                         |              |         |                              |              |         |
| Maxilla                         | 6/32 (18.7)             | 1            | 0.350   | 7/32 (21.9)                  | 1            | 0.886   |
| Mandible                        | 5/28 (17.9)             | 0.873        |         | 8/28 (28.6)                  | 0.02         |         |
| Sex                             |                         |              | 1.209   | 11/35 (31.4)                 | 1            | 0.404   |
| Male                            | 5/35 (14.3)             | 1            | 0.272   | 11/35 (31.4)                 | 1            | 0.404   |
| Female                          | 6/25 (24)               |              |         |                              |              |         |
| Smoker                          |                         |              |         |                              |              |         |
| No                              | 4/47 (8.5)              | 1            | 0.009*  | 11/47 (23.4)                 | 1            | 0.891   |
| Yes                             | 7/13 (53.8)             | 5.240        |         | 4/13 (30.8)                  | 0.019        |         |
| Opposing dentition status       |                         |              |         |                              |              |         |
| Natural/FPD/ISFCD               | 9/51 (17.7)             | 1            | 0.437   | 13/51 (25.5)                 | 1            | 0.951   |
| RPD                             | 1/4 (25)                | 0.604        |         | 0/4 (0)                      | 0.004        |         |
| Denture/overdenture            | 1/4 (25)                |              | 2/4 (50)|                              |              |         |

*The factors that were considered statistically significant (p < 0.05) in the univariate model.

According to a systematic review, occlusal overload, associated with parafunctional habits such as bruxism, was considered the primary factor related to mechanical complications[38]. Bruxers presented a higher prevalence of mechanical complications than non-bruxers (p<0.05) in the present study. Other studies have suggested that bruxism may be a risk factor for fractures of ceramics and, in general, for the need for technical interventions on implant-supported restorations[2]. The veneer fracture of acrylic teeth also presented a higher risk of occurrence when the ISFCDs were opposed to natural dentition or fixed prostheses in the present study. Other studies reported that prostheses opposed to either natural dentition/ fixed prosthesis presented lower survival rates than prostheses opposed to removable complete dentures or overdentures[2,39].

The occurrence of framework microcracks detected in the PEEK group may be related to the fatigue behavior of this high-performance polymer[40]. The appropriate interalveolar space and standardized procedure in the manufacturing process can account for the longevity of both prostheses and implants. Future research is necessary to determine the correct blending of reinforced materials to improve the fatigue behavior of PEEK.

Vertical bone loss in the PEEK group was significantly lower than that in the titanium group in the present study. The combination of PEEK frameworks with PMMA veneers may provide an elastic cushioning effect against chewing pressure. In contrast, metal/zirconia frameworks display a high modulus of elasticity, which may induce stress concentration at the alveolar crest among the implants[41]. Typically, an occlusal material-fabricated stiff framework allows the absorption and distribution of stress, which in turn ensures the longevity of both the prosthesis and implant[42]. It has been reported that the combination of the PEEK framework and resin veneers may dampen the occlusal forces and exert beneficial effects on implant-supported rehabilitation[43]. PEEKs with proper elasticity are also considered to benefit patients with TMJ complications. Another important proper-
ty of the PEEK framework is the soft tissue affinity around the implant. Biological complications are typically associated with low levels of oral hygiene. Hahnel et al. reported that the oral microflora attached to the PEEK surface was lower than that to zirconia, titanium, and PMMA. Other studies found that the adhesive plaques attached to PEEK healing abutments were reduced compared with titanium abutments, although a similar percentage of adhesive plaques was attached on the two surfaces in vitro studies. These findings suggest that high-grade polishing is a key factor in reducing plaque formation. Standard polishing (pre-polishing and high-grade polishing step by step) results in a surface featuring plaque resistance and improves shade stability, which are comparable to those of a ceramic material.

There are some limitations to the application of PEEK in oral implantology and prosthodontics. First, PEEK blanks have a grayish-brown or pearl-white opaque color and are unsuitable for monolithic aesthetic dental restorations, especially in the anterior region. Thus, veneering is required, but bonding to veneering composite resin materials remains a challenge because of the complex chemical structure of PEEK. Moreover, in contrast to titanium, PEEK has very limited inherent osteoconductive properties. Although unmodified PEEK is considered a bioceramic material, there has been no conclusive evidence of the osteoconductive effects of PEEK in vivo and in vitro. Furthermore, the fact that PEEK is less stiff and flexes implies an increase in width in the areas of the titanium sleeve for a minimum of 6 mm buccolingual width to compensate for flexion, as it represented a weak point. The mechanical properties can be influenced by the addition of different compound materials such as carbon fibers (CFR-PEEK). Further research and clinical trials are required to explore this material and possible modifications for further dental applications.

The limitations of the present study include the fact that this was a retrospective study, with only a single center, a short sample, and a lack of randomization. Furthermore, the diagnosis of bruxism was based on self-report of clenching/grinding during sleep or during wakefulness, plus the inspection part of several clinical examinations during the treatment, without examination by electromyography and/or polysomnography. Further research should focus on long-term and randomized studies to fully confirm the validity of the PEEK framework and PMMA veneers in implant dentistry.

5. Conclusion

Within the limitations of this retrospective study and the number of participants, implant-supported fixed prosthesis with PEEK framework and PMMA veneers can provide good prognosis for edentulous patients. Further long-term, large sample size, and randomized studies are warranted to evaluate the clinical effectiveness of this novel treatment option.

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Conflict of Interest

The authors declare that they have no conflicts of interest with the contents of this article.

References

[1] Maló P, de Araújo Nobre M, Borges J, Almeida R. Retrievable metal ceramic implant-supported fixed prostheses with milled titanium frameworks and all-ceramic crowns: retrospective clinical study with up to 10 years of follow-up. J Prosthodont. 2012;21:256–64. https://doi.org/10.11151/1532-849X.2011.00824X, PMID:22339902
[2] Chrzanovic BR, Kisch J, Larsson C. Retrospective evaluation of implant-supported full-arch fixed dental prostheses after a mean follow-up of 10 years. Clin Oral Implants Res. 2020;31:634–45. https://doi.org/10.1111/clr.13600, PMID:32249972
[3] Torsello F, di Torresanto VM, Erccoli C, Cordaro L. Evaluation of the marginal precision of one-piece complete arch titanium frameworks fabricated using five different methods for implant-supported restorations. Clin Oral Implants Res. 2008;19:772–9. https://doi.org/10.1111/j.1600-0501.2008.01555.x, PMID:18720557
[4] Pozzi A, Holst S, Fabbri G, Tallarico M. Clinical reliability of CAD/CAM cross-arch zirconia bridges on immediately loaded implants placed with computer-assisted/template-guided surgery: a retrospective study with a follow-up between 3 and 5 years. Clin Implant Dent Relat Res. 2015;17(suppl 1):e86–96. https://doi.org/10.1111/cid.12132, PMID:23910539
[5] Zoidis P, Papathanasiou I, Polyzois G. The Use of a Modified Poly-Ether-Ether-Ketone (PEEK) as an Alternative Framework Material for Removable Dental Prostheses. A Clinical Report. J Prosthodont. 2016;25:580–4. https://doi.org/10.1111/jopr.12325, PMID:26216668
[6] Jin H, Teng M, Wang Z, Li X, Liang J, Wang W, et al. Comparative evaluation of BioHP and titanium as a framework veneered with composite resin for implant-supported fixed dental prostheses. J Prosthodont. 2019;12:383–8. https://doi.org/10.1016/j.prosdent.2019.03.003, PMID:30982624
[7] Toth JM. Biocompatibility of Polyaryletherketone Polymers. PEEK Biomaterials Handbook. 2012, p. 81–92.
[8] Kurtz SM, Devine JN. PEEK biomaterials in trauma, orthopedic, and spinal implants. Biomaterials. 2007;28:4845–69. https://doi.org/10.1016/j.biomaterials.2007.07.013, PMID:17686513
[9] Stawarczyk B, Eichberger M, Uhrenbacher J, Wimmer T, Edelhoff D, Schmidlin PR. Three-unit reinforced polyetherketone composite FDPs: influence of fabrication method on load-bearing capacity and failure types. Dent Mater. 2015;34:7–12. https://doi.org/10.1016/j.dental.2013.345, PMID:25311236
[10] Najaee S, Zafar MS, Khurshid Z, Siddiqui F. Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. J Prosthodont Res. 2016;60:12–9. https://doi.org/10.1016/j.jpor.2015.10.001, PMID:26520679
[11] Zoidis P. The all-on-4 modified polyetherketone treatment approach: A clinical report. J Prosthodont. 2018;19:516–21. https://doi.org/10.1016/j.prosdent.2017.04.020, PMID:28709679
[12] Dawson JH, Hyde B, Hurst M, Harris BT, Lin WS. Polyetherketonetekone (PEKK), a framework material for complete fixed and removable dental prostheses: A clinical report. J Prosthet Dent. 2018;119:867–72. https://doi.org/10.1016/j.prosdent.2017.09.008, PMID:29195815
[13] Maló P, de Araújo Nobre M, Moura Guedes C, Almeida R, Silva A, Sereno N, et al. Short-term report of an ongoing prospective cohort study evaluating the outcome of full-arch implant-supported fixed hybrid polyetherketone-acrylic resin prostheses and the All-on-Four concept. Clin Implant Dent Relat Res. 2018;20:692–702. https://doi.org/10.1016/j.clr.2016.1266, PMID:30101132
[14] Ji TJ, Kan JYK, Rungcharassaeng K, Roe P, Lozada JL. Immediate loading of maxillary and mandibular implant-supported fixed complete dentures: a 1- to 10-year retrospective J Oral Implantol. 2012;38:469–77. https://doi.org/10.1563/AADF-JOI-D-11-00027, PMID:21942324
[15] Lobbezoo F, Ahlberg J, Claroos AG, Kato T, Kayano K, Lavigne GJ, et al. Bruxism defined and graded: an international consensus. J Oral Rehabil. 2013;40:2–4. https://doi.org/10.1111/j.1365-2528.2012.021262
[16] Sateia MJ. International classification of sleep disorders-third edition: highlights and modifications. Chest. 2014;146:1387–94. https://doi.org/10.1378/chest.14-0970, PMID:25367475
[17] Mombelli A, Oosten MAC, Schürch E, Jang NP. The microbiota associated with successful or failing osseointegrated titanium implants. Oral Microbiol Immunol. 1987;2:145–51. https://doi.org/10.1111/j.1399-302X.1987.tb00298.x, PMID:3507627

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