Fracture Resistance of Zirconia, Polyetheretherketone, and Polyetherketoneketone Implant Abutments After Aging

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Purpose: This study aimed to assess the fracture resistance of zirconia (Zr), reinforced polyetheretherketone (PEEK), and polyetherketoneketone (PEKK) implant abutments restored with glass-ceramic crowns after thermomechanical aging. Materials and Methods: Zr, reinforced PEEK, and PEKK titanium base abutments were divided into three groups (n = 10). CAD/CAM maxillary central incisor crowns were fabricated using monolithic lithium disilicate and luted to the abutments using resin cement. The specimens were thermomechanically aged (1.2 × 10⁶ cycles, 49 N, 5°C to 55°C). After testing fracture strength and determining fracture patterns, statistical analyses were made using the one-way analysis of variance (ANOVA) and Tukey post hoc tests (α = .05). Results: Fracture resistance of the PEKK abutments (541.90 ± 68.49 N) was significantly lower than the Zr (780.65 ± 105.77 N) and reinforced PEEK (741.09 ± 99.84 N) abutments (P = .000). A significant discrepancy was not detected between the reinforced PEEK and Zr abutments. Failures usually formed due to crown or abutment fracture, plastic deformation of the titanium base or screw fracture in the Zr group, crown fracture or separation of the abutment-crown complex from the titanium base in the reinforced PEEK group, and abutment fracture without crown deformation in the PEKK group. Conclusion: After thermomechanical aging, the reinforced PEEK abutments exhibited similar fracture resistance to the Zr abutments. All abutment types withstood the physiologic occlusal forces typical for the oral anterior region. Before considering them as alternative esthetic implant abutment materials, further in vitro and clinical studies are needed to determine their long-term performance. Int J Oral Maxillofac Implants 2021;36:332–340. doi: 10.11607/jomi.9007

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The success of implant-supported prostheses is not limited to osseointegration. Ensuring optimal esthetic outcomes, especially in the maxillary anterior region, is a critical factor.1,2

Titanium is used as a standard abutment material that provides reliable and biologically compatible frameworks for crowns due to its superior biomechanical properties.3 Nevertheless, the metallic color of titanium combined with highly translucent restoration materials creates a blue-gray reflection, particularly in the anterior region of patients with a thin gingival profile, adversely affecting the esthetic look.4–6 Ceramic abutments can be considered as alternatives to titanium abutments,7 although zirconia abutments are strong enough to withstand the occlusal forces in the anterior region and are esthetically successful. It has been reported that titanium abutments show approximately twice as much fracture resistance compared with one-piece zirconia abutments.5 In particular, at the implant-abutment joint, reducing the diameter of one-piece zirconia abutments may result in reduced strength and increased tendency to break.8 Therefore, it has been suggested to use zirconia abutments in combination with titanium bases.9–12 However, while ceramic materials are very resistant to compressive forces, they are not strong enough for tensile forces. They are extremely rigid, and laboratory procedures require precision, especially in screw-retained restorations, due to the potential for catastrophic fractures during function.9–11,13 In addition, the success of the restoration is highly dependent on the implant connection type or restoration design (screw retained or cement retained).14–16 and zirconia causes more extensive wear on the implant interface compared with titanium.17

In recent years, high-performance thermoplastic polymers with biomechanical and biocompatible materials have been studied as alternatives to titanium and ceramic abutment materials. Polyaaryletherketones (PAEK) constitute a semi-crystalline thermoplastic polymer family characterized by high-temperature stability and high mechanical strength.18–20 Polyetheretherketone (PEEK) is a member of the poly(aryletherketone)
family, and it is a special thermoplastic polymer that is commonly used in orthopedics and traumatology due to its favorable chemical stability, corrosion resistance, mechanical properties, temperature resistance, hydrolysis resistance, and good biocompatibility.\textsuperscript{18,19,21} In addition to these properties, it also has the ability to absorb the forces occurring during chewing due to its 4-GPa elastic modulus, with the result of causing less force transmission to the peri-implant region and preventing crestal bone resorption.\textsuperscript{22,23} PEEK was reinforced by adding 20\% (v/v) ceramic fillers with “0.3–0.5 mm grain size,” and this enabled the material to gain superior polishing properties.\textsuperscript{24} It is used as a healing cap, implant, abutment, crown, and framework material in dental applications.\textsuperscript{19,25–27} It can be manufactured by using CAD/CAM technology or by pressing from granules and pellets.\textsuperscript{19} The grayish and dull appearance of the material restricts its monolithic use for crowns. Thus, veneering is required to obtain an aesthetic appearance.\textsuperscript{28} Poly-etherketoneketone (PEKK) material is another high-performance biocompatible polymer, belonging to the same family of polymers as PEEK.\textsuperscript{28} PEKK has a higher compressive strength of up to 80\% compared with the unreinforced PAEK material.\textsuperscript{29} Due to the higher ketone group in its structure, PEKK has a higher melting temperature and a better shock absorption capacity compared with PEEK.\textsuperscript{28–30} This polymer is frequently preferred in the medical industry because of its superior biocompatibility properties. It is used as a primary transplantation material and an alternative to titanium in orthopedics.\textsuperscript{18} PEKK (246 MPa) has a similar compressive strength as dentin (297 MPa) but has a lower elastic modulus (5.1 GPa) compared with dentin (18.6 GPa).\textsuperscript{31} The possibility of producing different grades of hardness also allows the use of PEKK in a variety of applications, which may include crystallized PEKK use in fixed prostheses or amorphous PEKK use in removable prostheses.\textsuperscript{32} PEKK has been used as an implant material, as a postcore, and as a framework material in removable and fixed prostheses in studies.\textsuperscript{28,33–35} Although a PEKK abutment produced with a titanium base is commercially available, no scientific information on it was found in the literature.

In order to achieve esthetically desirable results, appropriate implant abutments should also be restored with crowns that have high translucency.\textsuperscript{7} Lithium disilicate glass-ceramic, which has high mechanical properties, is more esthetic than zirconium, especially in single crown restorations.\textsuperscript{36–38} This ceramic can be manufactured as monolithic to eliminate the risk of the fracture of veneering materials. Thus, they can better resist the maximum occlusal forces reported as 190 to 290 N for the anterior region.\textsuperscript{39,40}

In the literature, the information on the long-term use of PEEK and PEKK as implant abutment material is limited. Therefore, the goal of this in vitro study was to evaluate the fracture resistance and fracture pattern of zirconia, reinforced PEEK, and PEKK abutment materials restored with glass-ceramic crowns after thermomechanical aging, representing 5 years of clinical function. The hypothesis tested was that the fracture resistance and type would not be significantly different among the groups.

**MATERIALS AND METHODS**

A power analysis was carried out by software (G*Power 3.1, Heinrich Heine University). As a result of the analysis, the total specimen size was calculated as 27 (n = 9) for each group with 0.81 effect size (f), 95\% power (1-\(\beta\) err prob), and 0.5 error probability. According to the data obtained, the number of specimens in this study was decided as 30 (n = 10).

Thirty screw-retained implant abutments (diameter of 3.5 mm and a length of 9.0 mm) and analogs (diameter of 4 mm and a length of 14 mm) were used with an internal hexagonal length of 2.2 mm and a cuff height of 3 mm (Sky Implant, Bredent Medical). The abutments were classified in three groups of 10 abutments as follows: zirconia abutments with prefabricated titanium base (control, group Z), reinforced PEEK abutments with prefabricated titanium base (group R), and PEKK abutments with prefabricated titanium base (group P; Fig 1).
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Group Z: Zirconia Abutments
The abutments in group Z were esthetic hybrid zirconia abutments (Sky Implant, Bredent Medical). The inner surface of the prefabricated zirconia abutments was sandblasted at a pressure of 2 bars, while the outer surface of the titanium base was sandblasted at a pressure of 3 bars with 110 μm Al₂O₃ per the recommendations of the manufacturer for cementation. Then, sandblasted surfaces were treated with a primer (MKZ Primer, #482357, Bredent Medical) for 30 seconds, dried with air, and cemented with dual-cure composite cement (DTK adhesive, #465079, Bredent Medical).

Group R: Reinforced PEEK Abutments
This group consisted of prefabricated BioHPP elegance implant abutments (Bredent Medical). PEEK hybrid abutments were produced using the “for 2 press” system, which was specially developed by the manufacturer to prevent the occurrence of gaps between the titanium base and the abutment.

Group P: PEKK Abutments
In this group, a new abutment of equivalent size was designed with reference to BioHPP elegance abutments via CAD software, and abutments were produced by using PEKK CAD/CAM blocks (Pekkton, #0000318197, Cendres+Métaux) in the milling machine (Yena D30, Yenadent). Then, the titanium bases (Sky Implant, Bredent) were screwed into the implant analogs. PEKK abutments and titanium bases were sandblasted (2 bars for the PEKK abutment and 3 bars for the titanium base; 110 μm Al₂O₃). PEKK bond (Anaxblend, #201800206, Anaxdent) was applied to the abutments’ intaglio surfaces resting on the titanium bases, and a metal bonder (Anaxblend Metal Bonder) was applied to the titanium bases’ outer surfaces. PEKK and titanium bases were luted with Multilink Hybrid Abutment cement (Ivoclar Vivadent AG, #P1712001201). All procedures were completed in compliance with the recommendations of the PEKK material’s manufacturer for titanium base bonding.

For the standardization of the dynamic loading procedure, each specimen was placed in an acrylic resin (Technovit 4071 Heraeus Kulzer, #R010040). The specimens were positioned at a 30-degree angle to the vertical plane through special metal plates to reflect the clinical occlusal contact in the anterior region per ISO 14801 norms (Fig 2). When the polymerization of acrylic was completed, all abutments were screwed to the analogs and tightened at a torque value of 25 Ncm. After 10 minutes, it was rescrewed to prevent the loss of preload. The screw holes were closed with Teflon tape and flowable composite. CAD/CAM software (3Shape Dental System) was used to fabricate 30 monolithic crowns of lithium disilicate. Among the specimens prepared for the design of the crowns, one specimen was chosen from each study group, and the crown was designed in equal dimensions (11-mm length, 8.5-mm width) for each study group to fit the definitive maxillary central incisor. On the crowns’ palatal surfaces (3 mm below the incisal edge), a concave space was designed for the diameter of the antagonist ball to be used in the dynamic loading test, and the cingulum was shaped.

No preparation was made in order to prevent weakening of the material in the prefabricated abutments.

A total of 30 identically shaped crowns were produced by a milling machine (Coritec 550i, imes-icore) for each group by using semi-sintered glass-ceramic blocks (IPS e.max CAD, #U18179) reinforced with lithium disilicate. Subsequently, sintering and glazing procedures of the manufactured crowns were completed per the manufacturer’s suggestions.

Following the surface treatments of the abutments and the crowns (in line with the recommendations of the manufacturers; Table 1), the crowns were luted under a constant load of 50 N, using dual-cure resin cement (Panavia V5, #000038, Kuraray Noritake Dental). The excess luting cement was removed from the margins, and then the restorations were light polymerized (Elipar S10, 3M ESPE) from the palatal and labial surfaces for 30 seconds. All the cemented specimens were stored for 24 hours at 37°C until the thermomechanical loading test.

All specimens were thermomechanically aged at 5°C to 55°C for 1.2 x 10⁶ cycles, representing 5 years of clinical function by using a dwelling time of 60 seconds, a...
During the thermomechanical loading, specimens were examined two times a day for failures and recorded with a video camera. After thermomechanical loading, all specimens were examined under a stereomicroscope (Euromex NexiusZoom Range) with a magnification of ×12.5 to detect any failure. Then, a compressive load was applied by a crosshead with a speed of 0.5 mm/min to find the maximum fracture resistance using a universal test machine (Lloyd LRX, Llyod Instruments). Following the ISO 14801 norms, the force was applied at a 30-degree angle from the palatal surface using a 6-mm-diameter stainless-steel ball. In order to ensure a homogenous distribution of force, 0.5-mm-thick aluminum foil was placed between the stainless-steel ball and the specimens. The value of the fracture strength for each specimen was recorded using software.

To define the types of fractures, the fractured specimens were examined under a stereomicroscope (Euromex NexiusZoom Range) with a magnification of ×12.5. After the fracture resistance tests, failure types were classified as follows according to the fracture types reported by similar studies in the literature:

- Failure mode 1: Crown fracture only
- Failure mode 2: Crown and abutment fracture
- Failure mode 3: Abutment fracture without any deformation in the crown
- Failure mode 4: Plastic deformation in the titanium base, screw fracture, no fracture in the crown and abutment
- Failure mode 5: Failure in the titanium base excluding the crown
- Failure mode 6: Separation of the abutment-crown complex from the titanium base

After completion of the tests, statistical evaluation was performed using the SPSS 22.0 (IBM SPSS Statistic 2013) program. The normal distribution of the obtained data was investigated with the Shapiro-Wilk normality test. One-way analysis of variance (ANOVA) was used to determine whether the difference among the groups was significant (a P value < .05 was considered significant). Comparisons between the two groups (multiple comparisons) were performed with the Tukey test as a post hoc test.

## RESULTS

At the end of the thermomechanical loading tests, no loosening of the screws or crowns, no screw fractures, and no visible deformations of the specimens were observed. The survival rate of the specimens after aging was determined as 100%.

The Shapiro-Wilk normality test and the Levene homogeneity test showed that the obtained data had normal distribution with homogeneity of variance. The statistical comparison between the groups with a normal data distribution was performed with the one-way ANOVA test, revealing a significant difference between the groups (df = 29, sum of squares = 560122.671, F = 19.003, P = .000). The mean values and standard deviations (SDs) are given in Table 2.

The mean values and SD for group Z, which had the highest mean fracture resistance, was 780.65 ± 105.77 N. This value was followed by 741.09 ± 99.84 N for group R and 541.9 ± 68.49 N for group P. It was found that group P displayed the lowest fracture resistance, and this value was statistically different from all of the other groups (P = .000). Group Z and group R did not exhibit significant differences.

Failure modes of the specimens are represented in Table 3. In group Z, crown and abutment fractures were observed in four specimens (40%), screw fractures and titanium base plastic deformations without any...
abutment deformation occurred in three specimens (30%), only screw and titanium base fractures were present in two specimens (20%), and a crown fracture was observed in only one specimen (10%; Fig 4). In group R, the crown-abutment complex was separated from the base in five specimens (50%). In the remaining five specimens (50%), a crown fracture was seen. Abutment fracture or screw fracture was not found in the specimens (Fig 5). In group P, abutment fractures without any deformation in the crown were found in six specimens (60%). In three specimens (30%), only a crown fracture was observed. In one specimen (10%), the PEKK abutment was separated from the titanium base in the absence of any crown, abutment, or screw fractures (Fig 6). Similar to group R, no deformations or fractures were seen in the screw fracture or the titanium base.

**DISCUSSION**

Ceramic abutments with esthetic advantages have become increasingly popular for implant-supported restorations. Despite their esthetic superiorities, they have some limitations, such as lower fracture strength and tensile strength compared with metals, and they require highly sensitive processing and application stages.6

Esthetic abutment materials are a very active field of research. High-performance polymeric materials may be an alternative to ceramic with their biocompatibility, color, better stress distribution, shock absorption capacity, and compressive resistance.20,25,45

In this study, fracture resistance of Zr, reinforced PEEK, and PEKK implant abutments restored with lithium disilicate crowns was investigated after thermomechanical
The null hypothesis of the study that there would be no statistically significant difference in the fracture resistance values among the groups was refuted. The results showed that group Z (780.65 ± 105.77 N) and group R (741.09 ± 99.84 N) had a significantly higher fracture resistance than group P (541.9 ± 68.49; P < .001). Group Z and group R did not exhibit significant differences.

In the literature, the reported range of the maximum occlusal force in the anterior region is from 190 N to 290 N.39,40 In the present study, after thermomechanical aging, which simulated 5-year clinical use and static loading following it, the lowest breaking strength value was 492.9 N (Table 2), which was considerably higher than the values reported for the maximum forces in the anterior region. Accordingly, it can be concluded that Zr, PEKK, and reinforced PEEK abutments can resist the physiologic occlusal forces. The data obtained from these materials in the literature are consistent with the results of the present study.13,26,43,45

In the literature, although there are many studies about the mechanical properties of zirconium abutments, information about reinforced PEEK and PEKK abutments is very limited. In the studies, PEEK abutments are usually used as a provisional abutment material for implant-supported provisional crowns.25,26 PEEK and titanium implant abutments restored with composite resin crowns were used, and the fracture resistance of abutments placed in maxillary central, lateral, canine, and premolar tooth positions were compared in an in vitro study.25 It was reported that the fracture resistance of provisional crowns in PEEK abutments is similar to that of provisional abutments made of titanium, except for those used in the central incisor position.25 In another study, titanium, Ti-based zirconia, and Ti-based reinforced PEEK implant abutments were restored with glass-ceramic crowns, and their fracture resistances were compared after dynamic loading (100 N, 500,000 cycles) and thermal cycling aging.45 Fracture strength values were 787.80 ± 120.95 N for the Ti group (control), 623.93 ± 97.44 N for the Zr group, and 602.93 ± 121.03 N for the reinforced PEEK group. Similar to the present study, no statistically important discrepancy was found between the zirconia and reinforced PEEK groups.45 The reported fracture strengths were lower than the values found by the present study. This difference might have occurred due to the exposure of the specimens to different dynamic loading and thermal cycling processes.45

In clinical use, patients with a single tooth loss were restored with titanium base–reinforced PEEK abutments and lithium disilicate–reinforced glass-ceramic crowns, and after a 2-year clinical follow-up, successful esthetic and patient satisfaction were reported.20

PEKK has been reported to have superior properties, such as better long-term fatigue and greater compressive strength than PEEK.32–34 There are studies showing that PEKK is associated with successful outcomes in different fields of dentistry, including their use as
postcore, framework material in overdentures and removable prostheses. Although one commercial implant company produced a PEKK implant abutment (CERALOG Implant System, Camlog Biotechnologies) as a provisional and definitive abutment, no information about its use was found in the literature. In the present study, the fracture resistance of the PEKK abutments was found to be significantly lower than those of the reinforced PEKK and zirconia abutments after thermomechanical aging (1.2 × 10^6 cycles, 49 N, 1.6 Hz). This might be due to the use of the PEKK material without employing fillers while reinforcing the PEEK material with 20% ceramic fillers. Also, manufacturing differences may have effects on the fracture resistance of specimens.

The choice of restorative components, such as implant abutments, and the assessment of the connection type are factors that affect long-term success. In previous studies, it was concluded that the implant-abutment connection type might change the fracture strength and fracture type of the abutment. The meta-analysis comparing the fracture strength values after fatigue tests and cyclic loading showed that the internally connected abutments had a significantly higher fracture strength value than the externally connected abutments. In another study, restorations with cement-bonded internal connections in anterior crowns were reported to have higher fracture strength. Therefore, as in many other studies, internal connection types and cemented abutments were preferred in this study.

Lithium disilicate–reinforced glass-ceramics can be produced in different colors and translucency levels with optimum esthetic appearance by heat pressing or CAD/CAM techniques. These ceramics can be manufactured as a monolithic, eliminating the risk of separation between the layers after the veneering process. Furthermore, these ceramics have high bending strengths from 300 to 400 MPa and high fracture strengths with excellent optical properties. Thus, these crown materials were preferred as monolithic crown material in all groups in this study.

In order to increase the fracture strength of silica and polymer infiltrating ceramics, the use of adhesive resin cement with high compressive strength is recommended in cement-retained implant-supported prostheses. The use of cement in combination with 10-methacryloyloxydecyl dihydrogen phosphate (MDP) increases the shear bond strength of zirconia due to the interaction between the cationic surface of zirconia and the hydroxyl groups of MDP. In similar studies, various dual-cure adhesive cement types were used in combination with MDP (Panavia F2.0, Panavia SA). It was reported that Panavia V5 exhibited better bonding strength than Panavia F2.0. Unlike Panavia F2.0, Panavia V5 has a new, amine-free redox initiator system that improves bonding and provides long-term color stability. In this study, Panavia V5 resin cement based on MDP and dual-cure adhesive was used for the cementation of the crowns.

The PEEK surface is inert, and additional adhesive systems must be used to increase the resin bonding strength of the PEEK surface. It has been reported that methyl methacrylate (MMA) can constitute a sufficient bond to PEEK. In this study, according to the implant manufacturer and previous studies, a bonding agent (Visio.link) that contains MMA monomers penterythritol triacrylate (PETIA) and dimethacrylate was used to activate the PEEK and PEKK abutment surfaces before crown cementation. It has been reported that MAA has positive effects on PEEK bonding strength, and the dimethacrylate monomers bond both to the 2-carboxyl group and the composite resins.

The dynamic loading test was considered to be reliable in determining clinical performance, survival rate, and reliability of materials before they are recommended for clinical use. According to the data in the literature, 1-year use of the materials in clinical conditions corresponds to an average of 250,000 cycles in the chewing simulator. With 1.3- to 1.8-Hz chewing frequency, every 0.6- to 1.1-second cycle is considered within physiologic limits. Accordingly, 1.2 × 10^6 dynamic loading and simultaneous thermal cycling (5°C to 55°C, 60 seconds) with 1.6-Hz frequency and 49-N load were applied to the specimens in the present study. During dynamic loading, no failure was observed in any specimen.

In a similar study, titanium, aluminum, and zirconia implant abutments restored with silicate-based crowns were evaluated after thermomechanical aging. The zirconia abutment group’s mean fracture resistance was found to be 443.6 N. This value is lower than the results of the present study. This difference could be explained by the use of abutments with different diameters and thicknesses or crowns made of different types of materials. In another study, the fracture loads of aluminum and zirconia abutments restored with glass-ceramic crowns were evaluated under in vitro conditions without aging, and the fracture resistance of the crowns was found to be 280.1 N and 737.6 N for aluminum and zirconia implant abutments, respectively. The fracture resistance of the zirconia abutment group was found to be close to the results of the present study.

The type of fracture at the level of the abutment and screw that occurs in implant prostheses may affect the long-term success of the implant. In this study, when fracture types of groups were evaluated, screw and titanium base fractures were seen in group Z. However, these fracture types were not observed in groups R and P. In group R, either the abutment-crown complex was separated from the titanium base without any...
screw or abutment fractures, or crown fractures were observed. This can be attributed to the weak bond of the PEEK material to the titanium substructure, shock absorption capabilities, and low elastic modulus of the polymeric materials. The most common type of fracture in the PEEK group was abutment fracture without any deformation in the crown. It can be suggested that this difference was caused by the extra ketone group in PEKK, increasing the hardness and brittleness of the material. Researchers reported that the potential of PEEK abutments was high, but their success depended on the improvements in screw attachment and the quality of adhesion. The results of the present study are consistent with a previous study that reported that zirconia abutment restored monolithic lithium disilicate crowns exhibited more catastrophic fracture types, such as abutment, crown, or screw fracture, than the reinforced PEEK abutment restored with the same restorative material.

In the present study, the effects of connection and crown types on fracture resistance of implant-supported restorations were not examined. In future studies, these parameters may be evaluated. Before recommending PEEK or PEKK as alternative implant abutment materials, studies that not only evaluate these materials in terms of fatigue and static strength, but also in other aspects such as biologic and optical properties, are required.

CONCLUSIONS

Zirconia, reinforced PEEK, and PEKK implant abutments with a titanium base were found to have adequate fracture resistance in the anterior region against the maximum occlusal forces reported in the literature. Zirconia abutments showed more catastrophic fracture types than the reinforced PEEK and PEKK abutments. However, before considering them as alternative esthetic implant abutment materials, further in vitro and clinical studies are needed to determine their long-term performance.

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