Evaluation of composite resin core with prefabricated polyetheretherketone post on fracture resistance in the case of flared root canals

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The aim of this study was to use polyetheretherketone (PEEK) for the post material and evaluate the fracture load of six restoration patterns in teeth with flared root canals; composite resin core alone (Group R); glass fiber sleeve (Group S); PEEK post (Group P); glass fiber post (Group F); PEEK post in glass fiber sleeve (Group FS); glass fiber post in glass fiber sleeve (Group FS). In this study, cylindrical specimens were prepared and underwent three-point-bending test in a steady condition and after water immersion. In the loading test, the materials in clinical conditions using bovine teeth were evaluated. In the bending test, groups using glass fiber posts and sleeves decreased in strength after water immersion. In the loading test, Groups F, FS and PS showed higher fracture load than other groups. This study showed PEEK posts and glass fiber sleeves are recommended in the case of flared root canals.

Keywords: Composite resin core, Polyetheretherketone (PEEK), Flared root, Fracture strength

INTRODUCTION

Endodontically treated teeth have commonly been restored using posts and cores to aid in the retention of artificial crowns and to support the teeth. Cast posts and cores made from gold alloys have been used for years, as they have superior mechanical intensity and compatibility with dowel spaces1-3). However, because of the large elastic modulus difference between dentin and the post materials, an increase in stress concentration often causes vertical root fractures in teeth with such restorations9,10).

Recently, the use of composite resin materials for posts and cores has become a mainstream process because of the remarkable improvement in the mechanical properties and adhesion to root canal dentin compared to cast cores. Resin composites reinforce dentin because their flexural modulus is similar to that of dentin, which prevents root fractures8-10). Conversely, some studies5,11,12) have indicated that teeth restored using composite resin sometimes result in horizontal root fracture at the cervical region of the teeth; therefore, prefabricated glass fiber posts are often used in the restoration. Some studies have indicated that teeth structures restored using composite resin with prefabricated glass fiber posts show higher fracture strength than the teeth restored without post13,14). Moreover, composite resin restorations have commonly been selected for metal-free restorations because of their good aesthetics1).

However, the use of prefabricated glass fiber posts for teeth with flared root canals is debatable. One point of debate is that glass fiber posts have shown reduced strength in the case of water immersion. Komada et al.15) reported that prefabricated glass fiber posts were negatively influenced by water. Unlike cast posts and cores, glass fiber posts are compounds of glass and resin, that have many interfaces. An interface also exists between the composite resin core and the post. Moisture in the oral cavity is more likely to lead to a reduction in the strength of the posts and cores when multiple interfaces exist. As the deterioration advances under the influence of water, a reduction in the mechanical properties of the post and core is expected10). Thus, humidity could lead to failure of the restoration. However, in the oral cavity, dental materials are exposed to a wet environment and inevitably absorb water. Glass fiber posts are usually covered with composite resin cores and crowns, and they do not so often absorb water. Nevertheless, in clinical cases, there are some teeth that are covered with temporary crown and observed for several weeks. The temporary crown absorbs more water than the usually covered-crown. Resistance against water is therefore important to ensure the long-term durability of posts and cores.

In industry, super engineering plastics have been developed to replace metallic materials17). Engineering plastics have higher strength and heat resistance than existing plastic materials. In particular, polyetheretherketone (PEEK) has high chemical and thermal resistance, low water solubility, and superior biocompatibility. Even though PEEK has a low elastic modulus, it has high mechanical properties18-20). Thus, PEEK has been shown to be suitable for long-term restorations. In dentistry, PEEK is increasingly being evaluated for use in both fixed21-24) and removable25,26) prosthetics.

Another point of debate regarding the use of prefabricated glass fiber posts is the stress concentration and its effect. Cast posts and cores can easily cause root fractures of flared root canals because of the differences...
in the flexural moduli of the metal alloy and dentin. The stress concentration due to these differences acts on the dentin\(^4\,^5\,^7\). Flared root canals may also become predisposed to the effects of the wedging force of the cast posts and cores at the weakened coronal portion\(^8\). Therefore, the use of composite resin has been deemed appropriate for the restoration of such teeth in order to reinforce the thin, weakened root dentin. Some studies\(^9\,^10\) have reported that composite resin reconstitutes and reinforces teeth with thin, weakened root dentin. Okada et al.\(^6\) reported that the stress concentration on the cervical area of teeth restored using a composite resin post and core indicates, that strengthening the area surrounding the post space would be more effective than strengthening the center core. Recently, various fiber materials have been introduced in different types such as ribbon-like and tubular shape. Especially, some studies have reported that the combination of glass fiber post and glass fiber sleeve was effective in the case of flared root canals\(^27\,\,^28\).

In this study, PEEK was used for the post material rather than glass fiber, and the fracture load was evaluated in the case of teeth with flared root canals. Moreover, some types of restorations used tubular glass fiber sleeve because these sleeves were considered to strengthen the area surrounding the post space. Specifically, the aim of this study was to evaluate the fracture load of six restoration patterns using different post and sleeve configurations.

The hypothesis was that teeth with flared root canals would be reinforced by restorations using PEEK posts and glass fiber sleeves.

**MATERIALS AND METHODS**

*Three-point bending test*

1. **Experimental conditions**

The specimens in the three-point bending test are shown in Fig.1 and their corresponding materials are presented in Table 1.

![Fig. 1 Schematic long axial view of specimens in the three-point bending test (mm).](image)

(a) composite resin; (b) glass fiber sleeve; (c) PEEK post; (d) glass fiber post

| Experimental group | Core build-up materials  | Post materials                  | Sleeve materials                        |
|--------------------|--------------------------|----------------------------------|----------------------------------------|
| Group R            | Clearfil DC              | No post                          | No sleeve                              |
| Group S            | Clearfil Fiber Post No.5, (φ1.44 mm) (Kuraray Noritake Dental) | No sleeve                          |
| Group P            | Clearfil DC              | PEEK 450G, (φ1.5 mm) (Yasojima Proceed) (Tokyo, Japan) | No sleeve                              |
| Group F            | Clearfil DC              | PEEK 450G, (φ1.5 mm) (Kuraray Noritake Dental) | i-TFC Sleeve (φ2.0×50 mm) (Sun Medical, Tokyo, Japan) |
| Group PS           | Clearfil DC              | Clearfil Fiber Post No.5, (φ1.44 mm) (Kuraray Noritake Dental) | i-TFC Sleeve (φ2.0×50 mm) (Sun Medical) |
| Group FS           | Clearfil DC              | Clearfil Fiber Post No.5, (φ1.44 mm) (Kuraray Noritake Dental) | i-TFC Sleeve (φ2.0×50 mm) (Sun Medical) |
In the bending test, the cylindroid specimens were prepared to simulate the clinical dowel space of the specimens in the loading test. Six experimental groups were classified according to the type of restoration in the loading test: Group R, which was a composite resin core alone (Clearfil DC Core Automix, Kuraray Noritake Dental, Tokyo, Japan) (control); Group S, which used a prefabricated glass fiber sleeve (i-TFC Sleeve, φ2.0×50 mm, Sun Medical, Tokyo, Japan) with a composite resin core; Group P, which used a prefabricated PEEK post (PEEK 450G, φ1.50 mm, Yasojima Proceed, Tokyo, Japan) with a composite resin core; Group F, which used a prefabricated glass fiber post (Clearfil Fiber Post No.5, φ1.44 mm, Kuraray Noritake Dental) with a composite resin core; Group PS, which involved a prefabricated PEEK post (PEEK 450G, Yasojima Proceed) in a prefabricated glass fiber sleeve (i-TFC Sleeve, φ2.0×50 mm, Sun Medical) with a composite resin core; and Group FS, which involved a prefabricated glass fiber post (Clearfil Fiber Post No.5, φ1.44 mm, Kuraray Noritake Dental) in a prefabricated glass fiber sleeve (i-TFC Sleeve, φ2.0×50 mm, Sun Medical) with a composite resin core. The same groups were also analyzed under water immersion conditions: Group R.w, Group S.w, Group P.w, Group F.w, Group PS.w, and Group FS.w. The water immersion groups were immersed in 37°C deionized water for 30 days after fabrication.

2. Fabrication of the experimental specimens
The specimens were fabricated in vinyl chloride transparent tubes. The diameter of the tube was 5.0 mm externally and 3.0 mm internally. The length of the transparent tubes was adjusted to 18 mm. The tubes were embedded in an acrylic bar, and the bar was held in the gauge. An auto-mixed composite resin was injected to fill the tubes, and the posts and sleeves were inserted. Subsequently, the specimens were irradiated on the cross-sectional surfaces and all four sides of the acrylic bar using a light-curing unit (Blueshot, Shofu, Kyoto, Japan) with an intensity of 650 mW/cm² for 20 s. Prior to the curing process, the light intensity was measured thrice using a spectroradiometer (Jetlight Light Tester, J.Morita USA, CA, USA) to determine the output light power.

Twenty-four hours after curing, the tubes were incised, and the specimens were ejected. The length of the specimens was adjusted to 15 mm using a model trimmer (MODEL TRIMMER Y-230, YOSHIDA Trade Dental Distribution, Tokyo, Japan).

3. Three-point bending test
In this study, the specimens were subjected to three-point bending test to determine the maximum flexural strength of the post and core systems using a universal testing machine (Autograph AGS-H, Shimadzu, Kyoto, Japan). The shape of the two supports and the loading anvil of the testing machine was a semicircle with a diameter of 2.0 mm. The supports were spaced 10 mm apart. The force was applied perpendicularly at the center between the supports at a crosshead speed of 1.0 mm/min and the flexural strength was evaluated.

4. Statistical analysis
Two-way ANOVA and Tukey’s HSD test for multiple comparisons were used for statistical analysis of the flexural strength with a significance level of $\alpha=0.05$ (IBM SPSS Statistics for Windows, Version 25.0., IBM, Armonk, NY, USA).

**Loading test**

1. Experimental conditions
The post and core systems evaluated in this study are shown in Fig. 2 and the materials are shown in Table 1. Six experimental groups were analyzed in the loading test: Group R, Group S, Group P, Group F, Group PS, and Group FS. In all groups, the abutment of all specimens was uniformly shaped.
2. Specimen preparation
1) Tooth specimens and endodontic treatment
Sixty extracted bovine mandibular incisors with no cracks or fractures were used in this study. The specimens were preserved at −15°C. Before the experiment, they were defrosted at room temperature and divided into six groups of 10 specimens each.

All specimens were sectioned at 18 mm from the apical area using a low-speed diamond saw (Isomet Buehler, Lake Bluff, IL, USA), and the crowns were removed. Periodontal tissues around the roots were removed, and all root canals were shaped with K-files up to No. 120 (Files K, GC, Tokyo, Japan), and sequentially washed with 6% sodium hypochlorite solution and 2.5–3.5% hydrogen peroxide solution. After air-drying, the root canals were obturated with root canal obturation material (GUTTA PERCHA POINTS, GC) and a non-eugenol root canal sealer (Canals N, Showa Yakuhinkai Kako, Tokyo, Japan).

Twenty-four hours after endodontic treatment, all specimens were uniformly shaped with a small desktop lathe (KS-310, Toyo Associates, Tokyo, Japan) and their length was adjusted to 12 mm using a low-speed diamond saw to simulate human mandibular premolar roots. Then, a dowel space with a depth of 8 mm was prepared using a diamond instrument (H250 033, Horico, Berlin, Germany) under water cooling. The thickness of the specimen walls was adjusted to 0.8 mm at the cervical area by measuring with digital calipers (Digimatic Caliper, Mitutoyo, Kanagawa, Japan).

2) Core build-up
(1) Composite resin core (Group R)
A one-step bonding agent (Clearfil Universal Bond Quick, Kuraray Noritake Dental) was applied to the dentin in the root canal wall and the cervical shoulder regions of the root for 10 s. After applying the bonding agent, the root canals were air-dried, and the excess bonding agent was removed with paper points. Subsequently, the specimens were irradiated on the occlusal side using a light-curing unit (Blueshot, Shofu) with an intensity of 650 mW/cm² for 20 s. Prior to the curing process, the light intensity was measured thrice using a spectroradiometer (Jetlight Light Tester, J.Morita USA) to determine the output light power.

After the bonding procedure, an auto-mixed composite resin was injected using a slim auto-mixing tip to fill the dowel space, followed by irradiation from the light-curing unit on the occlusal, buccal, and lingual sides for 20 s each. The custom core form and their length was adjusted to 11 mm; the sleeves were cleaned with 40% phosphoric acid (K-Etchant Gel, Kuraray Noritake Dental) for 5 s, rinsed with deionized water, and air-dried. The sleeves were coated with a silane coupling agent (Clearfil Ceramic Primer, Kuraray Noritake Dental).

A one-step bonding agent (Clearfil Universal Bond Quick, Kuraray Noritake Dental) was applied to the dentin in the root canal wall, and was subsequently light-cured as described above. In the sleeves, an auto-mixed composite resin was injected.

After the bonding procedure, an auto-mixed composite resin was injected into the dowel space and sleeve, and the sleeve was inserted into the center of this space. Following irradiation from the light-curing unit on the occlusal, buccal, and lingual sides for 20 s each, the abutment was built up, adjusted, and stored as described above.

(3) PEEK post-reinforced composite resin core (Group P)
The length of prefabricated PEEK posts was adjusted to 11 mm. The posts were sandblasted with aluminum oxide particles (70 μm grain size, Hi Aluminas, Shofu) at 0.2 MPa, and a primer (BONDMER Lightless, Tokuyama Dental, Tokyo, Japan) was applied to improve their wettability.

A one-step bonding agent (Clearfil Universal Bond Quick, Kuraray Noritake Dental) was applied to the dentin in the root canal wall, and subsequently light-cured as described above.

After the bonding procedure, an auto-mixed composite resin was injected to fill the dowel space, and the post was inserted into the center of this space. Following irradiation from the light-curing unit on the occlusal, buccal, and lingual sides for 20 s each, the abutment was built up, adjusted, and stored as described above.

(4) Glass fiber post-reinforced composite resin core (Group F)
The length of prefabricated glass fiber posts was adjusted to 11 mm. The posts were cleaned with 40% phosphoric acid (K-Etchant Gel, Kuraray Noritake Dental) for 5 s, rinsed with deionized water, and air-dried. The posts were coated with silane coupling agent (Clearfil Ceramic Primer, Kuraray Noritake Dental).

A one-step bonding agent (Clearfil Universal Bond Quick, Kuraray Noritake Dental) was applied to the dentin in the root canal wall, and subsequently light-cured as described above.

After the bonding procedure, an auto-mixed composite resin was injected to fill the dowel space, and the post was inserted into the center of this space. Following irradiation from the light-curing unit on the occlusal, buccal, and lingual sides for 20 s each, the abutment was built up, adjusted, and stored as described above.
above.

(5) PEEK post and glass-fiber-sleeve-reinforced composite resin core (Group PS)
The length of the PEEK posts and glass fiber sleeves was adjusted to 11 mm. The posts were sandblasted with aluminum oxide particles (70 μm grain size; Hi Aluminas, Shofu) at 0.2 MPa, and a primer (BONDMER Lightless, Tokuyama Dental) was applied to improve wettability. The glass fiber sleeves were cleaned with 40% phosphoric acid (K-Etchant Gel, Kuraray Noritake Dental) for 5 s, rinsed with deionized water, and air-dried. The posts were coated with silane coupling agent (Clearfil Ceramic Primer, Kuraray Noritake Dental).

A one-step bonding agent (Clearfil Universal Bond Quick, Kuraray Noritake Dental) was applied to the dentin in the root canal wall, and subsequently light-cured as described above. In the sleeves, an auto-mixed composite resin was injected, and the posts were inserted.

An auto-mixed composite resin was injected to fill the dowel space, and the post and sleeve were inserted into the center of this space. Following irradiation from the light-curing unit on the occlusal, buccal, and lingual sides for 20 s each, the abutment was built up, adjusted, and stored as described above.

(6) Glass fiber post and glass-fiber-sleeve-reinforced composite resin core (Group FS)
The length of the glass fiber posts and glass fiber sleeves was adjusted to 11 mm. Both were cleaned with 40% phosphoric acid (K-Etchant Gel, Kuraray Noritake Dental) for 5 s, rinsed with deionized water, and air-dried. The posts and sleeves were coated with silane coupling agent (Clearfil Ceramic Primer, Kuraray Noritake Dental).

A one-step bonding agent (Clearfil Universal Bond Quick, Kuraray Noritake Dental) was applied to the dentin in the root canal wall, and subsequently light-cured as described above. In the sleeves, an auto-mixed composite resin was injected, and the posts were inserted.

An auto-mixed composite resin was injected to fill the dowel space, and the post and sleeve were inserted into the center of this space. Following irradiation from the light-curing unit on the occlusal, buccal, and lingual sides for 20 s each, the abutment was built up, adjusted, and stored as described above.

3) Embedded model
All specimens were embedded in acrylic-resin-infused aluminum rings by the following procedure, which is outlined in Fig. 3.

All prepared specimens were embedded into aluminum rings (length of 18 mm, diameter of 20 mm, thickness of 1 mm) filled with acrylic resin (Palapress Vario, Heraeus Kulzer, Hanau, Germany) using a gauge. Based on the biological width in standard anatomy, 2 mm of the root structure was maintained outside of the acrylic resin. A polysiloxane impression material (Correct Quick, Pentron, Wallingford, CT, USA) was used to surround each root to simulate the artificial periodontal ligament (thickness of approximately 0.25 mm). In all roots, 300 μm thick stainless steel plates were bonded to the buccocoronal bevel with cyanoacrylate adhesives (Aron Alpha, Toagosei, Tokyo, Japan) to prevent fracture of the composite resin core caused by the wedge effect.

3. Loading test
All specimens were fixed using the exclusive gauge (Fig. 4) and were loaded at 45° to the long axis with the ball
end (diameter of 2.0 mm) of a universal testing machine (Autograph AGS-H, Shimadzu). The loading test was conducted at a crosshead speed of 1.0 mm/min until fracture occurred. The maximum load causing fracture was recorded for each specimen.

4. Statistical analysis
One-way ANOVA and Dunnett’s T3 tests were used for the statistical analysis of the fracture loads, with significance level \( \alpha = 0.05 \) (IBM SPSS Statistics for Windows, Version 25.0., IBM).

RESULTS

Flexural strength
The arithmetic mean and standard deviation of the stress value in each group are presented in Table 2. The two-way ANOVA test results are shown in Table 3. Groups F and FS showed significantly higher flexural strength than other groups. In the water immersion test, Group FS showed higher flexural strength than the other groups. However, Groups S.w, F.w, and FS.w showed significantly lower flexural strength than groups S, F, and FS, respectively. Group P.w showed significantly higher flexural strength under water immersion.

Fracture load
The arithmetic mean and standard deviation of the stress value in each group are presented in Table 4. One-way ANOVA test results are shown in Table 5. Groups F, PS, and FS showed significantly higher fracture loads than other groups (\( p<0.05 \)).

### Table 2: Means (SDs) of the flexural strength of the experimental groups (\( n=10 \))

| Experimental group | Mean±S.D. (N) | Experimental group | Mean±S.D. (N) |
|--------------------|--------------|--------------------|--------------|
|                    | Not immersed |                    | Immersed     |
| R                  | 1,277.9±112.42 \( ^{ac} \) | R.w  | 1,378.95±250.43 \( ^{A} \) |
| S                  | 1,619±174.19 \( ^{d} \)  | S.w  | 1,389.13±175.98 \( ^{Ac} \) |
| P                  | 1,070.5±132.4 \( ^{ab} \) | P.w  | 1,278.73±120.96 \( ^{Ac} \) |
| F                  | 2,227.1±346.79 \( ^{e} \)  | F.w  | 1,696.75±101.01 \( ^{Bc} \) |
| PS                 | 1,348.35±140.89 \( ^{e} \)  | PS.w | 1,205.86±178.12 \( ^{C} \) |
| FS                 | 2,264.63±316.38 \( ^{ef} \) | FS.w | 1,967.24±217.32 \( ^{BDc} \) |

S.D., standard deviation
Groups with the same superscripted letters are not significantly different (\( p<0.05 \), Tukey’s HSD test).
* means significant difference between the immersed group and the not immersed group (\( p<0.05 \)).

### Table 3: Two-way ANOVA results (\( p<0.05 \))

| Source                     | Type III sum of squares | df | Mean square | F    | Sig. |
|----------------------------|-------------------------|----|-------------|------|------|
| Corrected model            | 17,550,386.530          | 11 | 1,595,489.685 | 38.431 | 0.000 |
| Intercept                  | 292,441,993.240         | 1  | 292,441,993.240 | 7044.134 | 0.000 |
| Type of restoration         | 15,049,155.446          | 5  | 3,009,831.089  | 72.499 | 0.000 |
| Immersion                  | 648,005.133             | 1  | 648,005.133  | 15.609 | 0.000 |
| Type of restoration*immersion| 1,853,225.951          | 5  | 370,645.190  | 8.928 | 0.000 |
| Error                      | 4,483,693.063           | 108| 41,515.677  | —     | —    |
| Total                      | 314,476,072.833         | 120| —           | —     | —    |
| Corrected total            | 22,034,079.593          | 119| —           | —     | —    |

| Immersion | Sum of squares | df | Mean square | F    | Sig. |
|-----------|---------------|----|-------------|------|------|
| Not immersed | Confrontation| 12,756,120.939 | 5  | 2,551,224.188 | 61.452 | 0.000 |
|           | Error         | 4,483,693.063 | 108| 41,515.677  | 19.974 | 0.000 |
| Immersed  | Confrontation| 4,146,260.458 | 5  | 829,252.092  | 41,515.677  |
|           | Error         | 4,483,693.063 | 108| 41,515.677  | 19.974 | 0.000 |
### Table 4  Means (SDs) of the fracture strength of the experimental groups (n=10)

| Experimental group | Mean±S.D. (N) |
|--------------------|--------------|
| R                  | 171.15±44.86 <sup>a</sup> |
| S                  | 207.50±22.90 <sup>a</sup> |
| P                  | 225.00±64.10 <sup>a</sup> |
| F                  | 376.60±87.85 <sup>b</sup> |
| PS                 | 407.45±103.51 <sup>b</sup> |
| FS                 | 477.20±124.04 <sup>b</sup> |

S.D., standard deviation
Groups with the same superscripted letters are not significantly different (p<0.05, Dunnett’s T3 test)

### Table 5  One-way ANOVA results (p<0.05)

| Source of variance | Sum of squares | df | Mean square | F     | p     |
|--------------------|----------------|----|-------------|-------|-------|
| Between groups     | 773,707.84     | 5  | 154,741.57  | 22.477| <0.01 |
| Within groups      | 357,984.25     | 52 | 6,884.31    | —     | —     |
| Total              | 1,131,692.09   | 57 | —           | —     | —     |

### DISCUSSION

#### Experimental conditions

The three-point bending of polymer-based luting materials is usually carried out following standard ISO 4049:2009 procedures<sup>29</sup>. In this study, however, cylindroid specimens were evaluated because, in the endodontically treated tooth, a circular dowel space is created using a Peeso reamer or RTP reamer; thus, to simulate the clinical dowel space, cylindroid specimens were prepared. We simply evaluated the post and core materials by flexural strength in a steady condition and the changes after water immersion.

In the loading test, the materials in clinical conditions were evaluated by restoring bovine teeth. Based on the hypothesis, we evaluated the fracture loads of teeth with the six types of posts and cores.

#### Flexural strength

Groups F and FS showed the highest flexural strength among all the groups, and the results were similar to those of the loading test. However, Groups P and PS showed lower flexural strength than other groups. PEEK has a low elastic modulus that was highly strained by the loading<sup>18-20</sup>. On the other hand, the composite resin was not strained as much as PEEK<sup>20</sup>. Therefore, differences in the amount of strain between the PEEK and composite resin could decrease the flexural strength. Moreover, the diameter of specimens in the bending test was 3.0 mm, which was smaller than the thickness of resin at the cervical area of the specimens in the loading test. As a result, the thin resin layer could be easily influenced by the differences in flexural moduli<sup>31</sup>.

Among the immersion samples, Groups S.w, F.w and FS.w showed significantly lower flexural strength. A previous study reported that some types of glass fiber posts decreased in the strength after water immersion<sup>13</sup>. In this study, all groups that decreased in strength after water immersion used glass fiber posts or sleeves, which agreed with the previous study. Glass fiber posts and sleeves were supposed to be intensely weakened by water immersion. In contrast, Group P showed higher flexural strength after water immersion, and Group PS was not weakened in spite of using glass fiber sleeves. Schwitalla et al.<sup>32</sup> reported no changes in the flexural strength of PEEK stored in a ringer solution; the flexural strength even showed an increasing tendency, which could be a result of the high stability of PEEK. In this study, the results of Groups P and PS agreed with those of the previous study. Although Group PS.w used glass fiber sleeves, there were no significant differences after water immersion, which was not possible in the case of glass fiber posts. The high stability of PEEK has been suggested to be very useful for dental materials. In oral treatments, there are many cases where water is intentionally applied, in addition to saliva or water in the breath. The results of this study showed that the use of PEEK for prefabricated posts should be useful in such harsh conditions.

#### Fracture load

Groups PS, FS, and F showed higher fracture loads than other groups, which clarified the durability of PEEK post and glass-fiber-sleeve-reinforced composite resin core.

Group R, which was restored with only composite resin, did not show a high fracture load. This result agreed with that of a previous report<sup>12</sup>. Therefore, a structure to joint the crowns and roots, such as posts or sleeves, was needed to reinforce teeth with flared root canals. In Group P, the teeth were not reinforced and...
showed a lower fracture load. Bitter et al.\textsuperscript{33} reported that, in the case of teeth with no coronal wall, post placement effectively constituted abutment construction, and teeth without post retention revealed a significantly higher failure rate compared with teeth restored with post retention. The elastic modulus of PEEK is about 4.1 GPa, which is lower than that of dentin (15–25 GPa).\textsuperscript{34-36} On the other hand, the elastic modulus of glass fiber posts is approximately 20 GPa,\textsuperscript{37} which is similar to that of dentin. In this study, the low fracture load of Group P indicated that the PEEK posts did not function well as posts.

The fracture load of Group S was as low as that of Groups R and P. Groups S and PS differed in terms of the material within the sleeve: composite resin or PEEK. There were no significant differences between Groups PS and FS; thus, it could be suggested the use of posts composed of materials other than composite resin reinforced the posts and cores.

Based on the results, a composite resin core reinforced with a glass fiber post, a glass fiber sleeve, and a PEEK post with a glass fiber sleeve showed high fracture loads. Combined with the results of three-point bending test, the PEEK post and glass-fiber-sleeve reinforced composite resin core is the most favorable for teeth with flared root canals.

Clinical benefits
In the loading test Group PS showed a fracture load as high as that of Group F, which is currently used in common dental treatments. This indicates that the new material, PEEK, is suitable and durable for use in prefabricated posts. In the three-point bending test, Groups F, and FS showed lower flexural strength after only 30 days of water immersion. This represents a great disadvantage for use in the oral cavity where water is constantly present. Glass fiber posts and sleeves are usually tested in the dowel space before build up, cleaned with phosphoric acid, and then rinsed with water. Thus, water can remain in the glass fiber sleeves. Moreover, the tops of glass fiber posts can be exposed during tooth preparation. Water is unavoidable in dental treatment, and residual water leads to the deterioration of cores when using glass fiber posts or sleeves. In contrast, PEEK posts do not present such issues. In particular, when treating teeth with flared root canals, some dentists choose extraction because of the high risk of root fractures. When the restoration procedure for such teeth is chosen, prostheses with a high risk of a poor long-term prognosis should be avoided. Super engineering plastics such as PEEK have superior mechanical and chemical properties and biocompatibility. Dental materials must withstand harsh intraoral conditions. Temperature variations, cyclic bite forces, and saliva can affect the mechanical and chemical properties of posts and cores. In such circumstances, PEEK is a useful and preferable post material.

However, PEEK has also undergone many improvements, particularly with regards to its color and low adhesion to other dental materials.\textsuperscript{38} Rikitoku et al.\textsuperscript{39} reported that 40 % SiO\textsubscript{2}-reinforced PEEK showed higher adhesion to composite resin cement. In consideration of this report, the fracture strengths of Groups PS, and P could be influenced by using PEEK reinforced with SiO\textsubscript{2}. Additionally, in this study, the fracture resistance was determined by loading with a heavy static force. However, in the oral cavity, teeth are rarely subjected to such heavy load, but instead are affected by repetitive light forces under mastication. Therefore, additional thermal cycle testing and cyclic loading test are needed to evaluate the durability of the post and core systems in future studies.

CONCLUSIONS
Within the limitations of this in vitro study, the following conclusion could be drawn:

1. Teeth with flared root canals were reinforced by restorations using glass fiber post, and the complex of posts and glass fiber sleeves.

2. In order to acquire the higher stability in the restorations of teeth with flared root canals, using PEEK post and glass fiber sleeve was recommended.

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REFERENCES
1) Dilmener FT, Sipahi C, Dalkiz M. Resistance of three new esthetic post-and-core systems to compressive loading. J Prosthod Dent 2006; 95: 130-136.

2) Hegde J, Ramakrishna, Bashetty K, Sirekha, Lekha, Champa. An in vitro evaluation of fracture strength of endodontically treated teeth with simulated flared root canals restored with different post and core systems. J Conserv Dent 2012; 15: 223-227.

3) Franco EB, Lins do Valle A, Pompéia Fraga de Almeida AL, Ruoh J, Pereira JR. Fracture resistance of endodontically treated teeth restored with glass fiber posts of different lengths. J Prosthod Dent 2014; 111: 30-34.

4) Fernandes AS, Dessai GS. Factors affecting the fracture resistance of post-core reconstructed teeth: a review. Int J Prosthodont 2001; 14: 355-363.

5) Goncalves LA, Vansan LP, Paulino SM, Sousa Neto MD. Fracture resistance of weakened roots restored with a transilluminating post and adhesive restorative materials. J Prosthod Dent 2006; 96: 339-344.

6) Okada D, Miura H, Suzuki C, Komada W, Shin C, Yamamoto M, \textit{et al.} Stress distribution in roots restored with different types of post systems with composite resin. Dent Mater J 2008; 27: 605-611.

7) Santos-Filho PC, Verissimo C, Raposo LH, Noritomi MecEng PY, Marcondes Martins LR. Influenf of ferrule, post system, and length on stress distribution of weakened root-filled teeth. J Endod 2014; 40: 1874-1878.

8) Hemalatha H, Sandeep M, Kulkarni S, Yakub SS. Evaluation of fracture resistance in simulated immature teeth using Resilon and Ribbond as root reinforcements. —an in vitro study. Dent Traumatol 2009; 25: 433-438.
9) Filo R, Cardash HS, Levin E, Assif D. Effect of core stiffness on the in vitro fracture of crowns, endodontically treated teeth. J Prosthodont Dent 2002; 88: 302-306.

10) Schwartz RS, Robbins JW. Post placement and restoration of endodontically treated teeth: a literature review. J Endod 2004; 30: 289-301.

11) Nakamura T, Ohyama T, Waki T, Kinuta S, Wakabayashi K, Mutobe Y, et al. Stress analysis of endodontically treated anterior teeth restored with different types of post material. Dent Mater J 2006; 25: 145-150.

12) Ozcan M, Valandro LF. Fracture strength of endodontically-treated teeth restored with post and cores and composite cores only. Oper Dent 2009; 34: 429-436.

13) Furuya Y, Huang SH, Takeda Y, Fok A, Hayashi M. Fracture strength and stress distributions of pulpless premolars restored with fiber posts. Dent Mater J 2014; 33: 852-858.

14) Maroli A, Hoecherl KAL, Reginato VF, Spazzin AO, Caldas RA, Bacchi A. Biomechanical behavior of teeth without remaining coronal structure restored with different post designs and materials. Mater Sci Eng C Mater Biol Appl 2017; 76: 839-844.

15) Komada W, Inagaki T, Ueda Y, Omori S, Hosaka K, Tagami J, et al. Influence of water immersion on the mechanical properties of fiber posts. J Prosthodont Res 2017; 61: 73-80.

16) Bitter K, Neumann K, Kielbassa AM. Effects of pretreatment and thermocycling on bond strength of resin core materials to various fiber-reinforced composite posts. J Adhes Dent 2008; 10: 481-489.

17) Kurtz SM, Devine JN. PEEK biomaterials in trauma, orthopedic, and spinal implants. Biomaterials 2007; 28: 4845-4869.

18) Skinner HB. Composite technology for total hip arthroplasty. Clin Orthop Relat Res 1988; 235: 224-236.

19) Rivard CH, Rhalmi S, Coillard C. In vivo biocompatibility testing of peek polymer for a spinal implant system: a study in rabbits. J Biomed Mater Res 2002; 62: 488-498.

20) Katzer A, Marquardt H, Westendorf J, Wening JV, von Foerster G. Polyetheretherketone —cytotoxicity and mutagenicity in vitro. Biomaterials 2002; 23: 1749-1759.

21) Costa-Palau S, Torrents-Nicolas J, Brufau-de Barberà M, Cabratosa-Termes J. Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: a clinical report. J Prosthodont Dent 2014; 112: 680-682.

22) 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: 580-584.

23) Zoidis P. Polyetheretherketone overlay prosthesis over high noble ball attachments to overcome base metal sensitivity: A clinical report. J Prosthodont 2018; 27: 688-693.

24) Zoidis P. The all-on-4 modified polyetheretherketone treatment approach: A clinical report. J Prosthodont Dent 2018; 119: 516-521.

25) Zoidis P, Papathanasiou I. Modified PEEK resin-bonded fixed dental prosthesis as an interim restoration after implant placement. J Prosthet Dent 2016; 116: 637-641.

26) Zoidis P, Bakiri E, Polyzois G. Using modified polyetheretherketone (PEEK) as an alternative material for endocrown restorations: A short-term clinical report. J Prosthet Dent 2017; 117: 335-339.

27) Xiong Y, Huang SH, Shinno Y, Furuya Y, Imazato S, Fok A, et al. The use of a fiber sleeve to improve fracture strength of pulpless teeth with flared root canals. Dent Mater 2015; 31: 1427-1434.

28) Kubo M, Komada W, Otake S, Inagaki T, Omori S, Miura H. The effect of glass fiber posts and ribbons on the fracture strength of teeth with flared root canals restored using composite resin post and cores. J Prosthodont Res 2018; 62: 97-103.

29) Borba M, Della Bona A, Cecchetti D. Flexural strength and hardness of direct and indirect composites. Braz Oral Res 2009; 23: 5-10.

30) Gloria A, Maietta S, Martorelli M, Lanzotti A, Watts DC, Ausiello P. FE analysis of conceptual hybrid composite endodontic post designs in anterior teeth. Dent Mater 2018; 34: 1063-1071.

31) Zogheib LV, Pereira JR, do Valle AL, de Oliveira JA, Pegoraro LF. Fracture resistance of weakened roots restored with composite resin and glass fiber post. Braz Dent J 2008; 19: 329-333.

32) Schwitalla AD, Spintig T, Kallage I, Müller WD. Flexural behavior of PEEK materials for dental application. Dent Mater 2015; 31: 1377-1384.

33) Bitter K, Noetzel J, Stamm O, Vaudt J, Meyer-Lueckel H, Neumann K, et al. Randomized clinical trial comparing the effects of post placement on failure rate of postendodontic restorations: preliminary results of a mean period of 32 months. J Endod 2009; 35: 1477-1482.

34) Ishikawa Y, Komada W, Inagaki T, Nemoto R, Omori S, Miura H. The effects of post and core material combination on the surface strain of the 4-unit zirconia fixed partial denture margins. Dent Mater J 2017; 36: 798-808.

35) Kinney JH, Marshall SJ, Marshall GW. The mechanical properties of human dentin: a critical review and re-evaluation of the dental literature. Crit Rev Oral Biol Med 2003; 14: 13-29.

36) Lawn BR, Deng Y, Lloyd IK, Janal MN, Rekow ED, Thompson VP. Materials design of ceramic-based layer structures for crowns. J Dent Res 2002; 81: 433-438.

37) Lamichhane A, Xu C, Zhang FQ. Dental fiber-post resin base material: a review. J Adv Prosthodont 2014; 6: 60-65.

38) Stawarczyk B, Thrun H, Eichberger M, Roos M, Edelhoff D, Schweiger J, et al. Effect of different surface pretreatments and adhesives on the load-bearing capacity of veneered 3-unit PEEK FDPs. J Prosthodont Dent 2015; 114: 666-673.

39) Rikitoku S, Otake S, Nozaki K, Yoshida K, Miura H. Influence of SiO2 content of polyetheretherketone (PEEK) on flexural properties and tensile bond strength to resin cement. Dent Mater J 2019; 38: 464-470.