Comparative Evaluation of Load-Bearing Capacity and Fracture Analysis of PEEK and Zirconia Three-Unit Fixed Dental Prostheses: An In Vitro Study

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Purpose: The purpose of this exploratory in vitro study was to compare and evaluate the load-bearing capacity (LBC) of ceramic-veneered zirconia and composite-veneered polyetheretherketone (PEEK) three-unit fixed dental prostheses (FDPs) with and without thermocycling (TC). Materials and Methods: The study included 40 samples of three-unit FDPs replacing mandibular first molars. The four groups included were: ceZIR (feldspathic ceramic–layered zirconia), ceZIR TC (feldspathic ceramic–layered thermocycled zirconia), cPEEK (composite-layered PEEK), and cPEEK TC (composite-layered thermocycled PEEK) (n = 10 per group). All frameworks were CAD/CAM milled. Ten PEEK and 10 zirconia samples were subjected to TC (6,000 cycles). All 40 FDP specimens were loaded by applying static load, using a universal testing machine. The maximum load required to fracture the specimens denoted the LBC. The comparison of LBC between the four groups was done by using two-way ANOVA with Tukey’s post-hoc analysis (α = .05). Results: There was no statistically significant difference between LBC of cPEEK and ceZIR (P > .001) without thermal aging. LBC values decreased considerably for thermally aged specimens. Statistically significant differences were observed between LBC of cPEEK TC and ceZIR TC (P < .001), cPEEK TC and cPEEK (P < .001), and ceZIR TC and ceZIR (P = .001). On fracture analysis, cPEEK showed delamination failures whereas ceZIR displayed catastrophic connector fractures. Conclusion: This comparative evaluation offers preliminary data highlighting substantial depreciation in the LBC of layered PEEK under simulated intraoral conditions, thus raising a question regarding the clinical longevity of layered PEEK multi-unit restorations. In contrast, feldspathic-layered zirconia can be suitable for use in posterior FDPs. Int J Prosthodont 2021 October 5. doi: 10.11607/ijp.7469. Online ahead of print.

Numerous esthetic systems have been developed to restore missing teeth. Among these esthetic systems, zirconia is a popular choice and high-performance polymers (HPP) are evolving materials.1 Zirconia has shown favorable outcomes in terms of mechanical and esthetic properties.2 However, clinical limitations of zirconia have been encountered due to its susceptibility to aging,3 low-temperature degradation,4 wearing of opposing natural dentition,5 and radioopacity precluding detection of secondary caries.6 In cases of zirconia layered with feldspathic ceramic, delamination of the ceramic veneer amounting to loss of structural durability is also a reported complication.7 In an attempt to search for improved extracoronal restorative materials, HPP have been extensively explored. HPP are a group of nonmetallic materials that retain their desirable mechanical and chemical properties in extreme environmental conditions.8 PEEK (polyetheretherketone), one of the pioneer high-performance polymers, has recently been advocated...
in numerous prosthetic and orthopedic conditions. The modulus of elasticity of PEEK is 4 GPa, and tensile strength is 120 MPa.\(^9\) Being compatible with dentin, a restoration made in PEEK minimizes the differential flexure between the prosthesis and the teeth.\(^10\) The low specific weight and low material fatigue of PEEK makes it a promising metal-free framework material.\(^11\) Despite being present for almost a decade, information related to the fracture resistance and mode of failure of multi-unit PEEK fixed dental prostheses (FDPs) is limited, especially in a set-up similar to intraoral conditions.

Clinical selection of a material for replacement of a posterior tooth largely depends on its fracture resistance or load-bearing capacity (LBC). The LBC of a chosen material must be highly compatible with the forces present in the oral cavity. Additionally, the property of load bearing should not deteriorate after use of the prosthesis with time. If this property is not closely matched or decreases unfavorably with time, it can lead to loss of integrity of the prosthesis, thereby disturbing the homeostasis of the stomatognathic system. Thus, LBC has a large role in determining the clinical longevity of the restoration.

The purpose of this exploratory in vitro study was to compare and evaluate the LBC of CAD/CAM-milled ceramic-veneered zirconia (ceZIR) and composite-veneered PEEK (cPEEK) three-unit FDP frameworks before and after thermocycling (TC). Furthermore, the two sets of frameworks were carefully scrutinized visually and through scanning electron microscope (SEM) to evaluate their fracture behavior. The null hypothesis was that no statistically significant difference exists in LBC of ceZIR and cPEEK three-unit FDPs before and after thermal aging.

**MATERIAL AND METHODS**

This in vitro study included a total of 40 samples of three-unit FDPs replacing mandibular first molars. A convenience sample size of 40 was selected, with four groups comprising 10 specimens each: ceZIR (feldspathic ceramic–layered zirconia), ceZIR TC (thermocycled zirconia), cPEEK, and cPEEK TC (thermocycled PEEK).

A three-unit FDP was designed for the missing first molar using the second molar and second premolar as abutments on a typodont (Frasaco). Both of the abutment teeth were prepared with an axial reduction of 1 mm, occlusal reduction of 1.5 to 2 mm, and a heavy chamfer finish line level with the gingival margin. The prepared typodont model was scanned using a digital scanner (Identica Hybrid, MEDIT). Computer data were used to design a three-unit FDP framework with a connector size of 3 x 3 mm and spheroidal pontic configuration (Fig 1). The design template was used for the standardized milling process (DentalCAM7, VHF). PEEK dental disks (Shade A2; Bredent) and zirconia blocks

![Fig 1](image-url) (a) Occlusal and (b) intaglio surface of computer-aided design of the three-unit FDP framework for a missing mandibular first molar.
(Shade A2; Cercon ht, Dentsply Sirona) were milled using four-axis milling (K4, VHF) to fabricate the three-unit FDP frameworks.

All of the PEEK milled frameworks (n = 20) were airborne-particle abraded with 50-µm powder for 45 seconds from a distance of 10 mm followed by cleaning in an ultrasonic bath for 5 seconds. A conditioning agent (Visio.Link, Bredent) was applied and light polymerized (bre.Lux Power Unit 2, Bredent) at 220 W/cm² for 90 seconds. Light-curing urethane dimethacrylate (UDM)-based composite (Visio.Lign, Bredent) was used to veneer the PEEK frameworks. A silicone index (Zetaplus, Zhermack) made from the wax-up on the master model was used to ensure uniform thickness of veneering composite on all specimens. The layering comprised intermediate polymerization of each increment for 90 seconds and final polymerization for another 90 seconds. Ten PEEK specimens were stored in air at room temperature before testing for LBC.

Twenty milled zirconia frameworks were sintered to full density at 1,500°C for 8.5 hours in the sintering unit (Zubler). The sintered zirconia frameworks were veneered using feldspathic porcelain (A2 Shade; Celtra ceram, Dentsply Sirona). The veneering process was carried out with the powder buildup technique, using three firing cycles. The silicone putty index was used to limit the veneering material thickness to 1 mm. Ten zirconia three-unit FDP specimens were stored in air at room temperature before testing for LBC.

Ten specimens of PEEK and zirconia each were subjected to thermocycling (without being bonded to the respective dies). The thermocycling was done by immersion of the specimens alone in temperature-controlled water tanks at 5°C and 55°C. Dwell time was 30 seconds and transfer time was 5 seconds for each cycle. There were 6,000 cycles performed each day for a period of 12 days.

In order to check the LBC of four specimens (ceZIR, ceZIR TC, PEEK, PEEK TC), metal laser-sintered dies of the prepared abutment teeth were fabricated. The digital impression of the scanned abutments was used for fabrication of the metal dies in chrome-cobalt alloy (Starbond CoS, Scheftner) with the direct metal laser-sintering process. Periodontal ligament resilience was simulated by coating the roots of the metal dies with double-layer-thick polyether material (Impregum, 3M ESPE). After coating, the metal dies with the coated roots were positioned using a 3D-printed photopolymerized repositioning jig (Form 2, Formlabs) in an acrylic resin base made up of self-polymerizing resin. It was placed in a manner such that the entire prepared abutment and part of the root surface (only 2 mm apical to the prepared margin) was exposed, simulating the biologic width.

Each specimen was luted with light-body addition silicone (Reprosil, Dentsply Sirona) to simulate the process of cementation on metal die abutments while measuring the LBC. The die spacer thickness was taken at 80 µm. In order to implement the loading test, a universal testing machine (UTM); UNITEST-10, ACME) was used. The UTM was connected to a laptop for reading the load measurements with built-in software (Fig 2). The stainless steel crosshead speed was 1 mm/minute. The force was transferred to the occlusal surface of the pontic along the long axis, via a metal plunger, with a diameter of 5 mm (Fig 3).

The amount of force increased gradually from zero to the point at which there was a sudden decrease in force. This sudden decrease was regarded as an indication of fracture of the sample. The maximum force attained before the decrease in force was recorded as the LBC in Newtons. Thus, the LBC was measured as a sign
of prosthesis failure. This included complete fracture of veneering material, complete fracture of framework, or delamination of veneering material.

Data were listed in a table and further analyzed with a statistical software program (SPSS Inc, version 21). Descriptive analysis was followed by tests of normality.
using Shapiro-Wilk test. Comparison of LBC between the four groups was done by using two-way ANOVA with Tukey post hoc analysis ($\alpha = .05$).

Using visual examination, crack location and fragmentation of core and/or veneering materials were also assessed as shown in Figs 4 and 5. Selected gold-sputtered fractured surfaces were further analyzed using a scanning electron microscope (SEM) (Fig 6).

RESULTS

All FDPs survived thermal aging without any visually apparent defects. The mean LBC observed was (in descending order): ceZIR (894.6 N ± 70.9 N), cPEEK (863.4 N ± 40.2 N), ceZIR TC (763.7 N ± 83.4 N), and cPEEK TC (501.8 N ± 64.7 N). A box and whisker plot (Fig 7) shows the comparative values of the LBC after computing the different quartiles for both of the samples.

The LBC of cPEEK was lower than the LBC of ceZIR. The difference was not statistically significant ($P = .725$, CI [–111.46, 49.16]). The LBC of cPEEK TC was lower than the LBC of ceZIR TC and the difference was statistically significant ($P < .001$, CI [–342.23, –181.60]). The LBC of cPEEK TC was lower than the LBC of cPEEK and the difference was statistically significant ($P < .001$, CI [–441.94, –81.31]). The LBC of ceZIR TC was lower than the LBC of ceZIR and the difference was statistically significant ($P = .001$, CI [–50.55, –211.17]).

The fractured three-unit FDPs were visually examined. For cPEEK, all 20 samples suffered delamination and/or chipping of the ceramic veneer at the pontic occlusal area. For ceZIR, the majority of the samples failed due to fracture at the distal connector region, with accompanying chipping of the veneering material.

SEM analysis revealed similar fracture pathways for all FDPs. In the group cPEEK there were internal cracks seen within the composite along with multiple porosities within the veneering material. For group ceZIR, fracture lines were observed initiating near the gingival aspect of the connector within the framework material (Fig 8).
DISCUSSION

The results of the study partially accept the null hypotheses. The difference in LBC of ceZIR and cPEEK three-unit FDPs was not statistically significant. After thermocycling, a statistically significant difference was observed between the LBC of ceramic-layered zirconia (ceZIR TC) and composite-veneered PEEK (cPEEK TC). A higher LBC was observed in ceZIR TC than in PEEK TC three-unit FDPs.

The mean biting force reported in the posterior region has been in the range of 700 N.\textsuperscript{17} The LBC of zirconia before and after thermocycling lie above the threshold suggested in the literature, thus making feldspathic-layered zirconia suitable as a material for three-unit FDPs in posterior replacements. The results were in agreement with other studies.\textsuperscript{18} However, there was a significant decrease in LBC after thermal aging. This may be attributed to a multitude of factors, such as low-temperature degradation or development of tensile stresses at the veneer framework junction or probable transformation from the tetragonal to monoclinic state.\textsuperscript{14,19}

The LBC of PEEK before thermocycling fulfilled the recommended value for the clinical scenario. However, the LBC obtained in the present study was much lower than that stated in previous studies. This may be due

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8a.png}
\caption{Fractured PEEK sample to be visualized by SEM. The section within the square denotes the section that was magnified by the SEM.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8b.png}
\caption{SEM image depicting the different fracture characteristics. Arrest lines and compression curls were observed while doing the fracture analysis. (Orange arrow, framework-veneer junction; brown arrow, compression curls; green arrow, arrest lines).}
\end{figure}
to the difference in the experimental design and use of monolithic frameworks. One study evaluated the LBC of nonveneered frameworks to be in the range of 1,300 N. Another study researched the effect of fabrication technique on fracture loads of monolithic PEEK FDPs and found LBC ranging from 1,700 to 2,300 N. Since veneered PEEK remains a clinical reality and benchmark because of esthetics, evaluation of the same is imperative. A striking contrast in LBC between nonveneered and veneered PEEK three-unit FDPs suggests the presence of inner tensile forces that generate postveneering due to unmatched elastic moduli and thermal expansion coefficient of PEEK and the veneering material. This becomes a primary concern, especially in areas of abnormal masticatory forces such as parafunction cases.

Moreover, the results of the present study suggest that the LBC of the thermocycled cPEEK group was considerably lower than the average biting force in the posterior region. These results emphasize the fact that subjecting layered PEEK to simulated oral conditions in the presence of fluid and temperature variation depreciates its LBC over time. This is probably due to water sorption and thermal deterioration of the methacrylate-based veneering composite and not the main framework. Thus, in the long term, three-unit FDPs made of veneered PEEK are not suitable to sustain occlusal loads satisfactorily. This finding serves as a future scope for clinical research to understand the behaviors of multi-unit FDPs in the oral environment.

Visual inspection of all the fractured samples was done for evaluation of crack location and fragmentation with respect to the veneering and core materials. PEEK mainly demonstrated adhesive failures due to chipping of the veneering material; ceZIR primarily had catastrophic framework failures at the connector region. Perhaps the connector size adopted in the present study (3 × 3 mm) accounted for the prominence of cohesive fractures amongst the zirconia samples. This was in accordance with other studies that showed a 50% increase in the stresses when the connector size changed from 4 to 3 mm in height. Thus, caution should be practiced while employing the material in areas of limited interocclusal space.

SEM analysis revealed the presence of internal cracks within the framework for group cPEEK along with multiple porosities within the veneering material, proving to be a plausible cause for the weakening and subsequent delamination of the veneering material. Fracture features such as arrest line, compression curls, fracture mirror, fracture origin, and hackle and twist hackle have been reported in the literature. In the present study, arrest lines and compression curls were observed while conducting the fracture analysis.

The limitations of the study include a small sample size. In this study, the FDPs were not cemented on the metal dies at the time of thermocycling and load bearing. The absence of cement may result in suboptimal bending forces and decreased damping effect during the application of load. The cement can, due to its thermal diffusivity and thermal conductivity, vary the temperature changes induced in the prosthesis during TC. Samples prepared by cementing the FDP to metal dies are recommended for TC and LBC analysis in future studies. The LBC was calculated using vertical occlusal forces. The use of such forces cannot predict the influence of lateral forces observed in the oral environment. As an elementary test, LBC is insufficient to completely simulate the clinical scenario. The study also does not account for cyclic mechanical loading, which simulates the chewing forces acting on prostheses to clinical scenarios. Future studies can incorporate the same to simulate the clinical conditions closely. The cobalt-chrome alloy, used for fabrication of the metal dies, has an elastic modulus of 200 GPa, which is higher than the elastic modulus of dentin (12 GPa). The fracture forces evaluated in the present study might have been higher than in clinical practice. Hence, use of a material with an elastic modulus similar to that of the teeth for the fabrication of the die would be recommended.

CONCLUSIONS

Within the limitations of the study, the following could be concluded:

- The LBC of the ceramic-layered zirconia three-unit FDPs, with and without thermal aging, was within the clinically acceptable range. Hence, the use of layered zirconia FDPs, when adhering to design specifications, can be indicated in the posterior regions.
- The process of thermal aging considerably reduces the LBC of composite-layered PEEK three-unit FDP samples. The decrease in fracture loads warrants caution, as the use of PEEK in the oral cavity can depreciate its mechanical properties, especially in the long term.
- Clinical trials with different FDP designs are necessary to provide more conclusive evidence of long-term reliability under in vivo conditions.

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REFERENCES


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