# Influence of occlusal and axial tooth reduction on fracture load and fracture mode of polyetheretherketone molar restorations after mechanical cycling

**Ayaka Shirasaki, DDS, Satoshi Omori, DDS, PhD, Chiharu Shin, DDS, PhD, Mina Takita, DDS, Reina Nemoto, DDS, PhD, and Hiroyuki Miura, DDS, PhD**

Department of Fixed Prosthodontics, Division of Oral Health Sciences, Graduate School of Medical and Dental Sciences, Tokyo Medical and Dental University, Tokyo, Japan

**Purpose:** To evaluate the influence of occlusal and axial tooth reduction on the fracture load of polyetheretherketone (PEEK) molar restorations after mechanical cycling (MC).
**Materials and Methods:** Occlusal and axial tooth reductions were defined to two-types with each, four-types of abutment tooth were prepared. Minimal occlusal reductions were 1.0-mm and 1.5-mm, and finishing lines were chamfer and deep-chamfer (1.0/C, 1.0/DC, 1.5/C, 1.5/DC). Four groups of PEEK restorations were duplicated. The thicknesses of restorations were same as each reduction. After cementation, one-half of the specimens were subjected to mechanical cycling (group MC); the others were stored without additional stress (group MC0). All specimens were loaded vertically until fracture. The maximum fracture loads were recorded and fracture modes were observed. Fracture loads were analyzed using Dunn's test with Bonferroni correction ($\alpha = 0.05$).
**Results:** There were no significant differences among specimens prepared the same way in groups MC0 and MC. In group MC, the fracture load of specimens with 1.0-mm occlusal reduction were significantly higher than that of 1.5-mm. The fracture loads of PEEK restorations in all preparations were higher than maximum occlusal forces and were not decreased after mechanical cycling.
**Conclusion:** The fracture loads of PEEK restorations in all preparations were higher than maximum occlusal forces and were not decreased after MC. Based on these results, PEEK restorations with less preparation can withstand long-term use in the oral environment.

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**Key Words:** fracture load, mechanical cycling, molar, polyetheretherketone, restoration, tooth preparation

## Introduction

Recent advances in digital technology and computer-aided design/computer-aided manufacturing (CAD/CAM) have been applied in the generation of dental crown restorations. Polyetheretherketone (PEEK) is a polymeric material that has found new applications in the field of CAD/CAM technology.

PEEK is a molecular chain consisting of an aromatic backbone interconnected by ketone and ether functional groups, and is classified as a semi-crystalline thermoplastic polymer. Favorable mechanical properties of PEEK include its high resistance to heat, impact, fatigue, and wear damage. Because of its high stability, PEEK is biocompatible, and exhibits low water solubility and absorption. In addition, PEEK has good machinability and abrasiveness, and is easy to process. Due to these advantages, PEEK is widely used as an industrial material. Also, PEEK has been used for orthopedic and spinal implants in the medical field [1,2].

There have been studies investigating clinical applications of PEEK. Stawarcryk et al. [3] and Taufall et al. [4] investigated the fracture resistance of PEEK in fixed partial dentures and concluded that PEEK could be potentially used as material to fabricate restorations and fixed partial dentures. It has also been reported that PEEK had the potential to be used as a framework for removable partial dentures [5]. There are also some studies on the application of PEEK to dental implants [6,7]. However, there have been few reports describing crown fabrication using PEEK, especially in molar regions.

Fracture resistance is one of the essential material properties required for molar restorations. Some studies have concluded that the fracture resistance increased as the occlusal thickness of the composite resin and ceramic restorations [8-11]. Fracture resistance is also related to the mechanical properties of materials. There are several factors that degrade the mechanical properties of prosthetics such as mastication causing mechanical stress. Attia et al. [12,13] reported that the fracture resistance of composite resin and all-ceramic CAD/CAM restorations decreased after mechanical cycling (MC) in vitro. It is important to evaluate the influence of mechanical cycling on dental materials in the laboratory to simulate mechanical stress and mastication. Liebermann et al. [14] examined the characteristics of PEEK after aging in different storage media, and concluded that PEEK could be used in long-term restorations. However, the behavior of PEEK restorations when mechanical forces are applied in the oral cavity remain unclear. The maximum occlusal force is reported to be between 914 N and 1280 N, although there are variations depending on age and sex [15,16]. The fracture load of molar restorations after mechanical cycling, therefore, should be higher than the maximum occlusal force.

Composite resin CAD/CAM-fabricated molar restorations have recently been introduced. In the studies about composite resin CAD/CAM restoration, the amount of the occlusal and axial reduction of abutment is ensured more than 1.5 mm respectively because of the mechanical property of composite resin [8,17-20]. Composite resin restorations required much amount of reduction of the abutment compared with the metal restoration to withstand maximum occlusal forces. However, sometimes reducing tooth structure may cause pulp injury [21] and it is required minimal reductions for crown preparations to conserve tooth structure. The adaptation of composite resin restorations has some limitations. On the other hand, there is a possibility that PEEK restorations with less preparation can withstand occlusal forces in the molar region because PEEK has many excellent mechanical properties. Therefore, PEEK is expected to expand the clinical applications for molar restorations.

The aim of this study was to evaluate the influence of occlusal and axial tooth reduction of PEEK molar restorations on fracture load after mechanical cycling to assess the utility of PEEK molar restorations in the oral environment.

## Materials and Methods

### Preparation

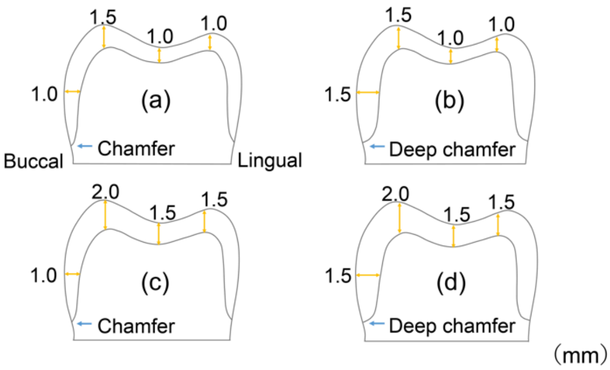
Artificial tooth models of mandibular right first molars (Anatomical Tooth Model B2-306, Nissin Dental Products, Kyoto, Japan) were prepared for crown restorations using a micromotor (Osada HL-C handpiece SH17, Osada Electric, Tokyo, Japan). The occlusal and axial tooth reductions were defined to two types (i.e., four types of abutment tooth were prepared). The occlusal reductions were prepared as follows: 1.0 mm reduction of the central fossa; 1.5 mm reduction of the functional cusp; 1.0 mm reduction of the non-functional cusp (group 1.0); 1.5 mm reduction of the central fossa; 2.0 mm reduction of the functional cusp; and 1.5 mm reduction of the non-functional cusp (group 1.5). The occlusal surface was prepared to as a V-shape, and reduction of the central fossa was minimal. The finishing line and axial tooth reductions were performed as follows: a chamfer finish line and 1.0 mm reduction of the maximum contour (group C); and a deep chamfer finish line and 1.5 mm reduction of the maximum contour (group DC). As a result, four types of abutment tooth groups were prepared. Each tooth preparation groups and designs were shown in Table 1 and Fig. 1.

### Fabrication of dies and restorations

Four groups of abutment tooth described above were used as master models. Impressions of these master models were made using two component silicone rubbers (KE1603, Shin-Etsu Chemical, Tokyo, Japan). An automixed composite resin (Clearfil DC core Automix One, Kuraray Noritake Dental, Tokyo, Japan) was injected into these impressions and light-cured for 20 s from the mesial, distal, buccal, lingual, upper, and lower sides using a dental curing light (Optilux501, KaVo Dental Systems Japan, Tokyo, Japan). Twenty-five composite resin dies were fabricated for each group: 24 composite resin dies for the experimental model, and one die for the scanning model.

**Table 1.** Tooth preparation groups

| Preparation design | | Axial reduction | |
|---|---|---|---|
| | | group C | group DC |
| Occlusal reduction | group 1.0 | 1.0/C | 1.0/DC |
| | group 1.5 | 1.5/C | 1.5/DC |



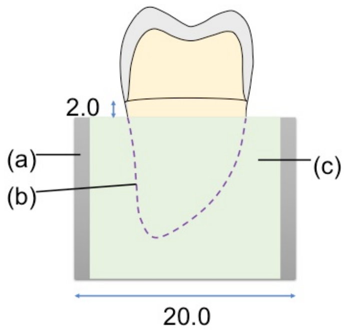




**Fig. 1** Schematic illustration of four groups of the abutment tooth
Occlusal reduction and axial preparation were listed in the following order: functional cusp; central fossa; non-functional cusp; finish line; maximum contour (mm).
(a) 1.0C (1.5; 1.0; 1.0; chamfer; 1.0), (b) 1.0DC (1.5; 1.0; 1.0; deep chamfer; 1.5), (c) 1.5/C (2.0; 1.5; 1.5; chamfer; 1.0), (d) 1.5/DC (2.0; 1.5; 1.5; deep chamfer; 1.5)
**Fig. 2.** Schematic illustration of the embedded model (mm)
(a) Aluminum tube, (b) Vinyl polysiloxane impression material, (c) Acrylic resin

Impressions of the fabricated dies for scanning model were made using vinyl polysiloxane impression material. (Duplicone, Shofu Inc., Kyoto, Japan). The impression was poured with dental stone (New Fujirock, GC Corp., Tokyo, Japan) and used as a cast for CAD/CAM scanning. These stone dies were scanned using a dental scanner (D2000 Dental Lab Scanner, 3Shape, Copenhagen, Denmark), and restorations were designed using CAM software (WorkNC Dental, Vero Software KK, Tokyo, Japan). Twenty-four restorations for each group were milled from PEEK blocks (Tokuyama Dental Corp., Tokyo, Japan) using a milling machine (DWX-50, Roland DG, Hamamatsu, Japan). The thicknesses of the restoration were same as the reduction of each occlusal and axial abutment tooth. All restorations were verified and adjusted to ensure an acceptable marginal and internal fit with an occlusal contact verification material (Bite-checker, GC Corp.).

**Cementation**

The PEEK restorations and composite resin dies were cleaned with alcohol. Additionally, internal surfaces of the restorations were airborne-particle abraded with aluminum oxide particles (70 μm grain size; Hi Aluminas, Shofu Inc.) at 0.2 MPa for 20 s at a distance of 10 mm. The restorations were ultrasonically cleaned with deionized water twice for 5 min each and dried with oil-free compressed air. After these treatments, primer (Bondmer Lightless, Tokuyama Dental Corp.) was applied to the internal surface of the restorations and composite resin dies for 10 s and dried with air. The restorations and composite resin dies were then luted with a resin-based luting agent (Estecem, Tokuyama Dental Corp.) according to manufacturer's instructions. The specimens were light cured from the mesial, distal, buccal, and lingual sides for 20 s each using a dental curing light (Optilux501, KaVo Dental Systems Japan). All specimens were stored at 37˚C and 100% humidity for 1 h, and, subsequently, in deionized water maintained at 37˚C for 24 h.

**Embedding**

All specimens were embedded into aluminum rings (15 mm length and 20 mm diameter) using acrylic resin (Palapress Vario, Heraeus Kulzer GmbH, Hanau, Germany). Each specimen was positioned 2 mm below the cement-enamel junction. To simulate the periodontal ligament (approximately 0.25 mm), each root was surrounded with a layer of vinyl polysiloxane impression material (CorrectPlus Bite Superfast, Pentron Japan, Tokyo, Japan) (Fig. 2). All specimens were stored in deionized water maintained at 37˚C for 24 h.

**Mechanical cycling**

All specimens in each group were divided into two groups (n = 12). One-half of the specimens were stored in deionized water at 37˚C without any additional stress (group MC0); the other half was subjected to mechanical cycling using an impact and abrasion tester (K655-05, Tokyo Giken Inc., Tokyo, Japan) (group MC). The specimens were subjected to a load of 50 N for 240,000 cycles at a frequency of 1 Hz in deionized water at 37˚C. The load was vertically applied to the central fossa of the specimens using a stainless steel rod with a ball end 4 mm in diameter. A rubber sheet (0.2 mm thick, Ivory Rubber Dams Thin, Kulzer GmbH) was placed between the rod and the occlusal surface.

**Load to failure test**

All specimens were loaded using a universal testing machine (Autograph AGS-H, Shimadzu Corporation, Kyoto, Japan) until fracture. The load was applied to the same point with mechanical cycling using a stainless steel rod with a 4-mm-diameter ball end at a cross-head speed of 1.0 mm/min. The maximum load causing fracture was recorded for each specimen and defined as the fracture load.

**Fracture mode**

After the loading test, the fracture modes of all specimens were observed using a stereoscopic microscope (APX, APS, Osaka, Japan) and classified into two groups: Class A, fracture of the restoration; Class B, fracture of the restoration and die.

**Statistical analysis**

Statistical analyses were performed using SPSS version 25 (IBM Corporation, Armonk, NY, USA). The Shapiro-Wilks test was used test for data normality in each of the fracture load test groups. Comparisons of all groups were statistically analyzed using Dunn's test with Bonferroni correction because the data were not normally distributed. All statistical analyses were performed at a 95 % level of confidence.

## Results

**Fracture load**

The means and standard deviations fracture loads of groupMC0 and groupMC are summarized in Fig. 3. The fracture loads of 1.0/C, 1.0/DC, 1.5/C, and 1.5/DC in group MC0 were 2,287.8 ± 164.6 N, 2,627.5 ± 220.5 N, 2,195.8 ± 132.3 N, 2,253.9 ± 162.9 N, respectively. The fracture load of 1.0/C, 1.0/DC, 1.5/C, and 1.5/DC in group MC were 2,564.0 ± 328.8 N, 2,977.9 ± 357.0 N, 2,201.5 ± 180.7 N, 2,210.1 ± 137.1 N, respectively. In group MC0, the fracture load of 1.0/DC was significantly higher than that of 1.5/C. In group MC, the fracture load of 1.0/C was significantly higher than that of 1.5/C, and the fracture load of 1.0/DC was significantly higher than that of 1.5/C and 1.5/DC. Statistical comparisons between fracture load of groups with and without mechanical cycling were summarized in Table 2. There were no significant differences between specimens prepared the same way in group MC0 and MC.

**Fracture mode**

The fracture modes for all groups are listed in Table 3. In groups MC0 and MC, the ratio of Class A in group C was higher than that of group DC. All specimens fractured with large deformations of the restoration. All specimens in Class B exhibited non-restorable root fractures. The lowest point of fracture was below the acrylic resin.

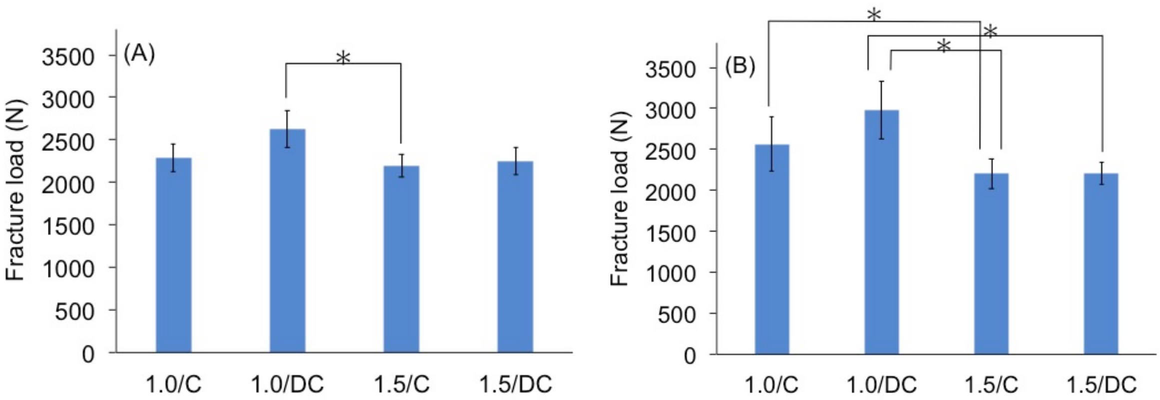



**Fig 3.** The fracture loads of groupMC0 (A) and groupMC (B)
Each value represents the mean and standard deviations. *Statistically significant difference ($p$ < 0.05) assessed by Dunn's test with Bonferroni correction

**Table 2** Statistical analysis results

| | groupMC0 versus groupMC* |
|---|---|
| 1.0/C | $p = 0.874$ |
| 1.0/DC | $p = 1.000$ |
| 1.5/C | $p = 1.000$ |
| 1.5/DC | $p = 1.000$ |

**Table 3** Fracture modes

| | groupMC0** | | groupMC** | |
|---|---|---|---|---|
| | Class A | Class B | Class A | Class B |
| 1.0/C | 12 | 0 | 8 | 4 |
| 1.5/C | 11 | 1 | 12 | 0 |
| 1.0/DC | 3 | 9 | 0 | 12 |
| 1.5/DC | 0 | 12 | 1 | 11 |

*Comparison between fracture load of without mechanical cycling (groupMC0) and after mechanical cycling (groupMC)
**Number of specimens: Class A, fracture of the restoration; Class B, fracture of the restoration and composite resin die

## Discussion

The mean fracture load of all groups of PEEK restorations was higher than 2,000 N. Braun et al. [15] and Varga et al. [16] measured maximum voluntary occlusal force in the molar region and reported a range of 914 N to 1,280.0 N. The fracture load of all groups with PEEK restorations was higher than the maximum occlusal force, which suggests that PEEK restorations can withstand the maximum occlusal forces in the molar region of the oral environment with dynamic loading. Recently, composite resin CAD/CAM technology has been applied to molar restorations. Although, there is a range in the fracture load of composite resin CAD/CAM restorations according to variation in preparation design and materials, the fracture load is reported to be from 1,200 N to

2,900 N [8,17-19]. These data are comparable with the fracture loads of PEEK restorations observed in the present study. In group MC, the fracture load of the 1.0/C was higher than that of the 1.5/C specimens, and the fracture load of the 1.0/DC was higher than that of the 1.5/C and 1.5/DC specimens. Using finite analysis, Bakhit et al. [22] investigated the fracture behavior of PEEK restorations when the load was applied to the center of the restoration surface, and reported that stress was directly transmitted to the top of the resin core because PEEK had a smaller elastic modulus compared with other materials. The elastic modulus of PEEK is lower than alloy, ceramics, zirconia, and composite resin, which are widely used in clinic. Furthermore, PEEK exhibits ductility and can accommodate large deformations during compression [2,23]. Jaekel et al. [24] investigated the behavior of PEEK using the small punch test and reported that PEEK crowns deformed in the area the load was applied. When vertical load is applied to PEEK, compressive stress occurs at the loaded surface and tensile stress occurs at the opposed surface. The amount of deformation of PEEK increases as the vertical distance from the load area increases. Micro cracks occur in the large deformation area and PEEK restorations fracture by the propagation of micro cracks. In this study, the amount of deformation of the restoration increased as occlusal reduction increased because the load was applied vertically. Therefore, the fracture load of group 1.5 was lower than that of group 1.0.

The load-to-failure test was performed after the PEEK restorations were cemented to dies. The elastic modulus of the restoration and die is related to fracture behavior. When the elastic modulus of the restoration is higher than that of the die, cracks occur at the restoration edge due to deformation of the die [10]. On the other hand, it is considered that the PEEK restorations are deformed earlier than the composite resin die because the elastic modulus of PEEK restorations is lower than that of the composite resin die.

The fracture load of the 1.0/DC was higher than that of the 1.5/C preparations in both the MC and MC0 groups. In our previous study, finite element analysis confirmed that stress concentrated on the die was higher as the axial thickness increased when the load applied to the PEEK restoration, which suggests that axial reduction is related to fracture load. However, the amount of occlusal reduction affected the fracture load more than the amount of axial reduction because there was no significant difference between 1.0/C and 1.0/DC, and between 1.5/C and 1.5/DC specimens.

Although mechanical cycling has an influence on the fracture load of composite resins and all-ceramic CAD/CAM restorations [13,25], the fracture load of PEEK restorations did not decrease after mechanical cycling. This suggests that PEEK restorations can withstand long-term use in the oral environment with dynamic loading.

In this study, the PEEK restoration represented a molar restoration. The preparation of 1.0/C was assumed to reflect a metal restoration and the preparation of 1.5/DC was assumed to reflect a composite resin CAD/CAM restoration. In recent studies, composite resin CAD/CAM technology has been applied to the fabrication of molar restoration. In these studies, the amount of occlusal and axial reduction of the die was ensured to be more than 1.5 mm because the mechanical properties of composite resins are inferior to metals. The amount of tooth reduction for composite resin CAD/CAM restorations is more than that for metal restorations [13,18-20]. It is recommended to remain a dentin thickness more than 0.5 mm to avoid causing pulp injury in the case of vital teeth [21]. Removal of tooth structure is limited to avoid pulp injury for young patients. Additionally, it is difficult to reduce the occlusal abutment without damaging the pulp when the interocclusal space is limited. Composite resin CAD/CAM restorations have some limitations to adaptation because it is difficult to preservation of tooth structure. On the other hand, the fracture load of PEEK restorations, which preparation of die was assumed to full metal restoration showed sufficient fracture strength. It is suggested that PEEK restoration is applied to many cases compared to composite resin CAD/CAM restorations. Reducing occlusal reduction of the abutment preparation would contribute to promoting to retention and resistance of the restoration.

The percentage of Class A in group C was higher than that in group DC. Cracks in the composite resin die extended to the root in all specimens of Class B. It was possible to repair when restoration fractures occurred without fracture of the die, which suggests that PEEK restorations with chamfer preparations can be repaired or retreated when fracture occurs. All restorations fractured with large deformations, which were observed at the region where force was applied. Our previous study confirmed that the stress concentrated to die when the axial wall of the PEEK restoration was thick, compared with cases in which the axial wall was thin. It has also been reported the PEEK restorations prevented stress in the marginal area of dentin [22], which is consistent with the results of the present study.

The supporting die structures in the present study were assumed to be vital teeth or a composite resin core. Supporting die structures, which have an elastic modulus similar to teeth, may be used to achieve results that more closely resemble to clinical conditions [26]. The elastic modulus of composite resin is 12-20 GPa, and that of dentin is 15-25 GPa [27-29]. The conditions of this study were close to clinical conditions because the elastic modulus of resin composite die was comparable to that of dentin.

Mechanical cycling with 1,200,000 cycles with a load of 50 N has been reported to be equivalent to 5 years of clinical use [30,31]. The number of mechanical cycles was assumed to one-year period. The applied load with mechanical cycling in this study was appropriate as a load assuming chewing forces in a clinical case because the mean masticatory forces during mastication and swallowing range from 0.9 N to 89.9 N [32]. And, a 0.2 mm thick rubber sheet was placed between the rod and the occlusal surface to avoid contact damage.

Thermal cycling has been reported to affect the reduction of the fracture load of composite resin CAD/CAM restorations [33]. In the present study, mechanical cycling was performed with vertical force and without any other aging procedures, such as thermal cycling, artificial saliva and mechanical cycling with lateral force. Therefore, further studies investigating the influence of other aging procedures are necessary to confirm whether PEEK restorations have sufficient long-term fracture resistance in oral environments.

**Conflicts of Interest**
The authors declare that there are no conflicts of interest related to the manuscript.

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Correspondence to:

Dr. Satoshi Omori
Department of Fixed Prosthodontics, Division of Oral Health Sciences,
Graduate School of Medical and Dental Sciences,
Tokyo Medical and Dental University (TMDU), 1-5-45, Yushima, Bunkyo-ku, Tokyo 113-8549, Japan
Fax: +81-3-5803-0201 E-mail: s.omori.fpro@tmd.ac.jp

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