Assessment of Biomechanical Behavior of Endodontically Treated Premolar Teeth Restored with Novel Endocrown System

Keywords

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ABSTRACT

Objective: Despite the increased popularity of endocrowns, there is no clear consensus considering their effectiveness to restore severely-destructed endodontically treated premolars. This study aimed to assess the biomechanical behavior of endodontically treated maxillary first premolars restored with a novel endocrown system compared to the conventional one. Materials and Methods: Twenty sound human maxillary first premolars were collected. After endodontic treatment, they were divided into 2 groups (n=10) according to the system used for endocrown fabrication. Group C (Control): conventional monolithic IPS e.max CAD endocrowns. Group P: novel bi-layered endocrowns (Pekkton ivory coping veneered with cemented IPS e.max CAD). All specimens were subjected to 10000 thermal cycles followed by 240000 dynamic load cycles. Surviving specimens were subjected to fracture resistance test followed by qualitative analysis using Stereomicroscopy and Scanning Electron Microscopy. Results: A significantly higher load was observed for Group P (1831.37 ± 240.69 N) than Group C (1433.47 ± 174.39 N) ($p < 0.001$). A statistically significant difference was observed considering the failure mode ($p = 0.036$), with more favorable fractures detected with Group P. Conclusions: The tested novel endocrown system improved the biomechanical behavior of the tooth/restoration complex in the restored endodontically treated maxillary first premolars. Clinical Significance: The tested novel endocrown system with a PEKK coping veneered with cemented IPS e.max CAD can be considered a promising option for restoration of severely-destructed endodontically treated premolar teeth. It can be considered as a conservative alternative option to the conventional treatment modalities.

INTRODUCTION

Rehabilitation of the endodontically treated teeth (ETT) with severe coronal damage presents a clinical challenge because the poor structural integrity caused by caries and/or cavity preparation leads to a greater risk of teeth fracture. The restorative material and prosthetic treatment options play a significant role in the longevity of both the restoration and the non-vital teeth.[1] A crown restoration built on a core part with its support from a root canal post is known as the common traditional treatment approach for ETT with coronal tooth loss. However, the application of such post causes root weakening with increased root fracture risk, as well as the perforation during the post space preparation.[2] Within the improvement of adhesive dentistry, endocrown

restorations have been developed as an alternative to post-core systems for the restoration of severely-damaged teeth.[1,2]

Endocrowns are monoblock restorations that combine the core structure with the crown restoration using both the macro-retentive support of the pulp chamber walls with the micromechanical retention of the adhesive cementation.[3] In fact, minimally invasive preparations, with maximal tissue conservation, are now considered "the gold standard" for restoring ETT. By following this rationale, endocrowns are applied as a prosthetic option in restoration of endodontically treated teeth with excessive tissue loss.[4] In addition to their role in the restoration of coronal anatomy, endocrowns have been known to allow sealing of root canal access, preventing bacterial microleakage that could possibly affect the favorable long-term prognosis of ETT. Additionally, during an endodontic failure, re-interventions can be performed more easily.[5]

The advantages of using endocrown restorations include also little dental structure preparation compared with post and cores, lack of intervention in the root canals, as well as less interfaces between each part of the restorations and the teeth. Compared with conventional crowns restored with a cast post and core or a fiber post and resin core, endocrowns have been proven more resistant to fracture. They are also straightforward with less clinical time, low cost, ease of application, and excellent esthetic properties. Therefore, endocrowns now represent an esthetic and conservative restorative alternative.[3,4,6] A systematic review and meta-analysis study regarding endocrown restorations demonstrated that endocrowns may perform similarly or better than the conventional treatments using intra-radicular posts, direct resin composites, or inlay/onlay restorations, exhibiting excellent clinical survival rates higher than 94% in up to 36 months follow-up.[7] They are particularly indicated in cases in which there is excessive loss of crown tissue, interproximal or interocclusl space is limited and traditional rehabilitation with post and crown is not possible because of inadequate ceramic thickness. In addition, they are also an alternative in teeth with short or atrophic clinical crowns, and calcified, curved or short narrow root canals that make post application impossible.[4]

Endocrown restorations have been introduced as a rehabilitation option for teeth with extensive coronary destruction that has been considered a challenge for restorative dentistry.[8] The endocrown preparation characterized with the conventional circumferential butt margin (no ferrule) allows the conservation of peripheral enamel, which is a key of success in strong improved adhesion leading to reduced marginal leakage,[9] better distribution of loading and high fracture resistance.[10] In spite of failure at greater loads, it was observed that ferrule with endocrown preparations causes a greater number of catastrophic defects in the tooth due to an existing lever in the dental root.[11,12] Also, it was reported that if the endocrown cementation is adhesive, reducing an amount of sound enamel represents an inappropriate situation since the adhesion between restorative material and tooth promoted by the enamel is superior in comparison to the dentin.[13]

An important area of interest is the choice of the restorative material to optimize the performance of such endocrown restoration.[9] Reinforced, acid-etchable ceramics are the materials of choice for endocrown fabrication that they provide sufficient mechanical strength withstanding the occlusal load with appropriate bond strength to the tooth substance.[3,14] Both pressable and machinable (CAD/CAM) ceramics reinforced with lithium disilicate are seemed to be the best material option due to their high mechanical strength, excellent tooth adhesion properties, and excellent esthetics.[14]

Although dental ceramics have several positive characteristics such as high compressive strength, natural appearance, good biocompatibility, and low plaque accumulation, they are sensitive to processing and application errors and still show lower bending and tensile strengths than metals.[15,16] When the ceramic material strength is exceeded, spontaneous fracture or chipping occurs because of its brittleness. The indications of polymers to be used in dentistry have expanded in recent years as an alternative to ceramics.[15]

Polyaryletherketones (PAEK) are high-performance thermoplastic polymers comprising of polyetheretherketone (PEEK) and polyetherketoneketone (PEKK). PEKK was presented more recently with great biocompatibility and has an 80% higher compressive quality and superior long-term fatigue properties than unreinforced PEEK.[14,17] Due to their acceptable fracture resistance, better stress distribution, and shock-absorbing ability, they are considered as alternative dental materials for metals and ceramics.[18-20] Moreover, it is gaining popularity due to its fabrication flexibility as it can be heat-pressed or milled. It has been utilized as an alternative material for dental implants, frameworks of partial removable dental prostheses, frameworks of partial and complete fixed dental prostheses, and implant abutments because of its lightweight and compatibility with diverse veneering materials.[14,21] It has comparable mechanical properties to that of natural dentition improving the biomechanical match between restoration and tooth and thus reducing the fracture risk.[11,22] It has a nearly similar compressive strength (246 MPa) to that of dentin (297 MPa), and also modulus of elasticity (5.1 GPa) nearly similar to dentin (18.6 GPa). On the other hand, the rigid lithium disilicate-reinforced ceramics with high elastic modulus (IPS e.max CAD = 95 GPa) transfer more and unfavorable stresses to the adjacent tooth structure. They are not sufficiently elastic to accompany the natural flexural movements of the tooth.[23,24]

There are limited clinical studies that supported the application of PEKK material in restorative dentistry.[21,25] A study used it as a framework material for complete fixed and removable dental prostheses.[21] Another study investigated veneered PEKK-made long-term temporary restorations during the initial phase of periodontal therapy. It was found that they improved the periodontal therapy and oral hygiene of patients, with high esthetical advantage and satisfaction for PEKK than veneered cobalt chrome restorations.[25]

No independent studies investigated the application of the novel, biomimetic high performance polymer PEKK as a coping for endocrown restoration. Only through a clinical report, Zoidis *et al.*[14] described the use of BioHPP (PEEK) framework material veneered with indirect light-cured composite resin for endocrown fabrication with an extensively damaged molar. After 22 months, the clinical evaluation diagnosed good endocrown retention and appearance with no signs of microleakage.

The question that remains to be replied is the reasonableness of endocrowns to restore endodontically treated premolars (ETPM). They were revealed more failure when used for premolars, likely due to their smaller adhesion area and greater crown height with more horizontally (non-axial) directed forces received compared to molars, which may impact fracture resistance.[3,5] To date and in spite of the expanded popularity of endocrowns, there is no clear agreement within the literature about which endocrown design with which material is the most effective treatment option for restoration of severely-destructed ETPM.[16,26] There is a lack of data around the effect of the endocrown system on the biomechanical behavior within the tooth/restoration complex of restored ETPM.[3] Moreover, there is no accessible laboratory evidence to effectively and successfully affirm the reliability of such a bi-layered endocrown system as a novel sort of restoration in ETPM.

Regarding to the previously mentioned information, this *in-vitro* study was performed to assess and analyze the biomechanical behavior of endodontically treated maxillary first premolar teeth restored with endocrowns fabricated using high performance polymer PEKK veneered with cemented lithium disilicate glass ceramic compared to conventional lithium disilicate glass ceramic endocrowns. The main tested null hypothesis was that the used novel endocrown system will improve the biomechanical behavior in the tooth/restoration complex of the restored endodontically treated maxillary first premolar teeth.

MATERIALS AND METHODS

This study followed all guidelines by a Local Research Ethics Committee and received approval no. 04111218. The materials used in this study are listed in Table 1. Twenty sound human bifurcated maxillary first premolars with completely formed roots, freshly extracted for a periodontal or orthodontic reason were collected from Oral and Maxillofacial Surgery Department, Faculty of Dentistry, Mansoura University. The teeth were selected with homogenous dimensions and morphology.[24,25,27,28] Cracked, carious, or restored teeth were excluded,[26,27,29,30] and teeth with widely-curved or atypically-shaped roots were also excluded.[3] All selected teeth were disinfected for one week using 1:10 diluted 5.25% sodium hypochlorite household bleach.[18] At room temperature and during all testing periods, the teeth were stored in distilled water to avoid dehydration.[1,30]

All teeth were decapitated parallel to the occlusal surface at a level 2 mm occlusal to the highest occlusal point of the proximal cemento-enamel junction (CEJ)[5,24,27] using a diamond linear precision saw blade mounted in a water-cooled, low-speed sectioning machine (IsoMet 4000).[3,5] By the same operator, all teeth were then endodontically treated using a NiTi rotary files system (Race/25 mm) according to manufacturer's instructions.[5] Canals were irrigated using 5.25% sodium hypochlorite liquid[3,26] and the smear layer was finally removed using 17% EDTA solution applied for 5 minutes.[1,5] Using lateral compaction technique, obturation of root canals was made to full working length and sealed with an epoxy resin-based sealer.[3,5,27,28] At this stage, kidney-shaped access cavities were partially filled with a layered flowable composite resin material (Nexcomp Flow A3) after application of a thin coat of a light-cured universal dental adhesive (All-Bond Universal).[3,24,27] This adhesive was worked into the cavity for 10-15 seconds, air-thinned for 10 seconds and light-cured for 10 seconds using a LED light-curing unit (Elipar DeepCure-S), according to the manufacturer's instructions. The roots of each selected tooth were embedded vertically along their long axes within acrylic resin blocks using a dental surveyor (Milling unit BF 2).[3,5,26,29,30] For all teeth, approximately 0.3 mm uniform layer of periodontal ligament (PDL) was simulated around roots using "Transitional Wax Technique" with a light-body of polyvinyl siloxane impression material (Harmony light fast setting).[22,31]

The selected teeth were randomly divided into 2 groups (n = 10) according to the system used for endocrown fabrication. Group C (Control): 10 teeth receiving monolithic lithium disilicate glass ceramic endocrowns (IPS e.max CAD). Group P: 10 teeth receiving bi-layered endocrowns with high performance polymer PEKK (Pekkton ivory) as a coping and lithium disilicate glass ceramic (IPS e.max CAD) as a cemented veneering.

In this study, CAD/CAM technology was utilized to perform a standardized endocrown preparation for all selected teeth. It included a process chain that comprises of scanning, designing, and milling phases. Firstly, each numbered block was trimmed from one aspect to provide a flat surface for fixation of a separate holder of an IPS e.max CAD block *(Figure 1)*. This holder was used to be identified later on by the milling system's calibration feature. A highly-sensitive 3D optical scanner (Identica hybrid) was then used to scan the acrylic resin block-holder assembly. A refractory scanning powder (D-SCAN Scanspray) was sprayed for precise imaging of the fixed metal holder. Special scanning software (colLab Scan, v2.0.0.4) was used until providing high-resolution scan data, as shown in *(Figure 2)*.

Using a dental CAD software (DentalDB 2.2 Valletta), the design for endocrown preparation for each scanned tooth was made. It included firstly smoothening and finishing of a circumferential butt margin[3,26,27] and then maintaining a central cavity with a depth of 4 mm,[26,27] axial wall internal taper of 6°[28,32] and a circular axial wall thickness of 2 ± 0.2 mm.[24,33] Internally, cavity

Table 1. Materials used in this study.

Material	Product name	Batch number	Composition	Manufacturer
(I) The endocrown material:				
1) Lithium disilicate glass ceramic	IPS e.max CAD (LT A2/C 14)	Y15163	- Main component: SiO_2 (57-80 wt%) - Other contents: Li_2O, K_2O, MgO, Al_2O_3, P_2O_5, ZrO_2, ZnO and coloring oxides	Ivoclar Vivadent, Schaan, Liechtenstein
2) High performance polymer PEKK	PEKKTON ivory milling blank (98.5/t20mm)	0000347597	- Polyetherketoneketone (PEKK) 90% - Titanium Dioxide (TiO_2) 10%	Cendres + Metaux SA, Biel/Bienne, Switzerland
(II) The luting system:				
1) Adhesive cementation system	**Duo-Link** Universal Kit (universal shade)	1800007808	A) Duo-Link Universal dual-cured resin luting cement: **Base**: Ytterbium Fluoride (10-20%), Bis-GMA (10-30%), UDMA (10-30%), Ytterbium Oxide-Silica (1-5%), Tetrahydrofurfuryl Methacrylate (1-5%), TMPTMA (1-5%), 3(Trimethoxysilyl)propyl-2-Methyl-2-Propenoic Acid (< 2%). **Catalyst**: Bis-GMA (10-30%), Dibenzoyl Peroxide (< 1%). B) All-Bond Universal light-cured dental adhesive: Bis-GMA (30-50%), Ethanol (30-50%), HEMA (10-30%), MDP (5-10%), water, initiators. C) Porcelain Primer pre-hydrolyzed silane primer: Ethanol (30-50%), 3-(Trimethoxysilyl) propyl-2 Methyl-2-Propenoic Acid (1-5%), Acetic Acid (< 1%).	Bisco Inc Schaumburg, IL, USA.
2) Ceramic etchant	Porcelain Etchant (9.5% HF)	1900002832	9.5% buffered hydrofluoric acid gel.	Bisco Inc Schaumburg, IL, USA.
3) Tooth etchant	N-Etch Etching Gel	X25230	Phosphoric acid (37 wt% in water), thickeners and pigments.	Ivoclar Vivadent, Schaan, Liechtenstein
4) PMMA & composite primer	visio.link	183158	Mixture of dimethacrylates, initiators and stabilizers; methyl methacrylate (40-60%), 2-propenoic acid reaction products with pentaerythritol (< 25%), (1-methylethylidene) bis [4,1-phenyleneoxy(2-hydroxy-3,1-propanediyl)] bismethacrylate (< 25%), diphenyl(2,4,6,-trimethylbenzoyl)-phosphine oxide (< 3%).	Bredent GmbH & Co. KG, Senden, Germany.

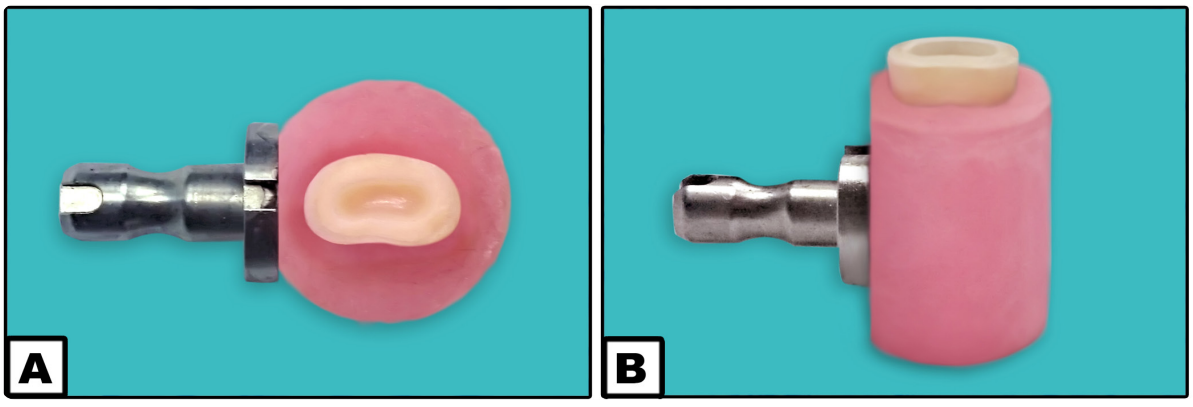

Figure 1: A separate holder of IPS e.max CAD block fixed to the acrylic resin block.

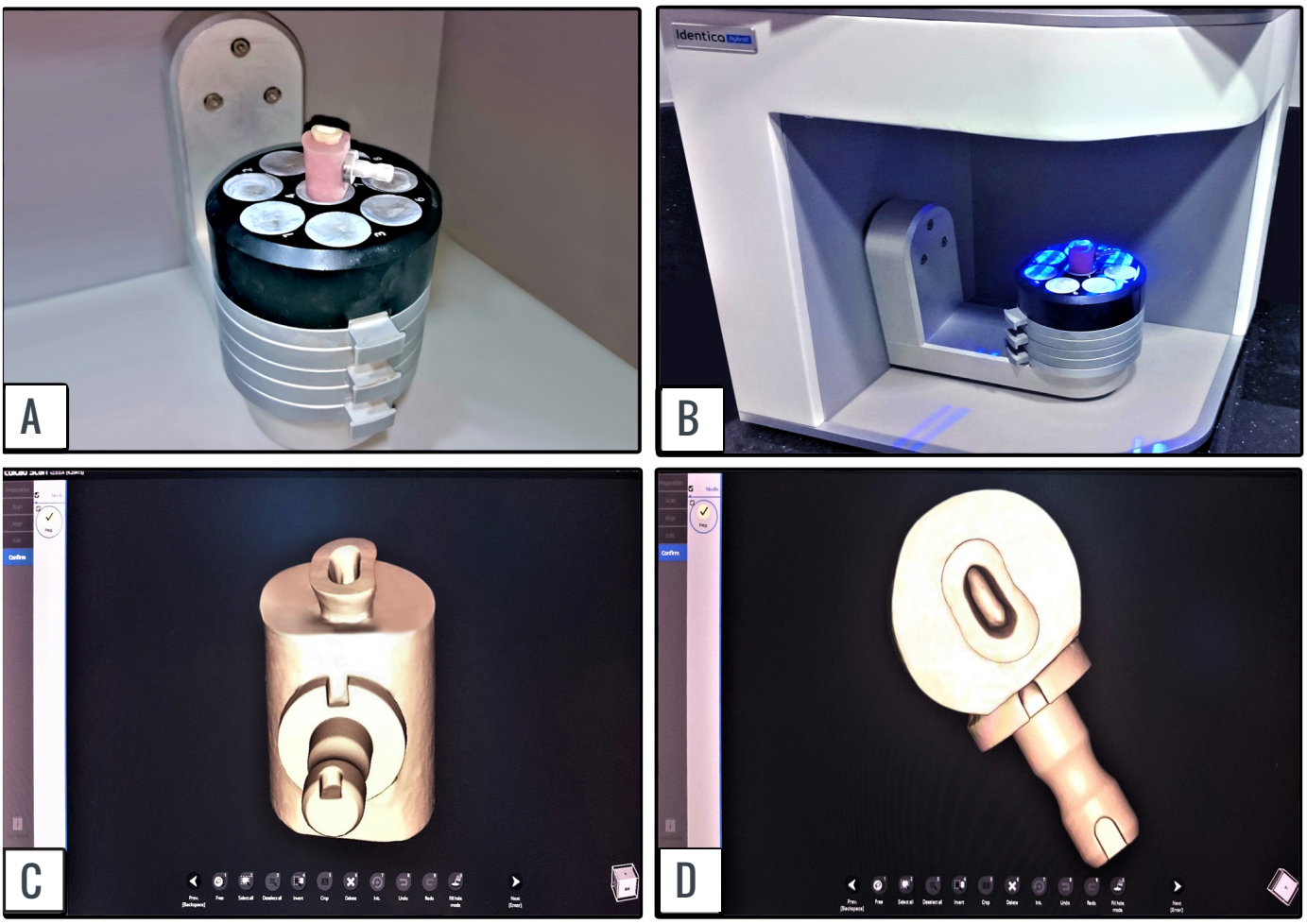

Figure 2: Scanning phase for CAD/CAM endocrown tooth preparation; (A) assembly fixed on a special multi-die plate, (B) scanning started, and (C and D) high-resolution scan data produced..

preparation was limited to removal of undercut areas and maintenance of anatomic configuration of the pulp chamber with smooth rounded internal line angles, as shown in *(Figure 3)*.[5,27]

After verifying the virtual design of endocrown preparation, this finished design was nested using a dental CAM system (MillBox, v2016/5 Full Expert). A first pre-milling tool path calculation for the initial scanned not designed block was completed with an appropriate specially-designed blank size (apex-3 / 28x28x28) selected to suit the dimensions of the tooth-holding acrylic block. Then, the designed block without holder was accurately positioned to precisely overlap the initial scanned not designed block. After that, the initial not designed block was removed and only the target designed block remained in position. Finally, it was simply transferred into dental CAM software (SUM3D Dental, version 5 Axes Full) for machining only the endocrown preparation design features from already scanned unprepared tooth through specific selected parameters. A 5-axis wet/dry milling machine (CORiTEC 250i touch) was used for wet-milling of teeth using diamond grinding tools (CORiTEC). Diamond 2.5 mm bur (T21/185909) was used for gross milling and diamond 1 mm bur (T22/180792) was used for finer adjustment. Each tooth took approximately 18-22 minutes to be milled and prepared completely.

After milling process for each tooth, the endocrown preparation features were revised and evaluated visually to assure maintenance of the original pulp chamber configuration, using probe palpation to check smooth finishing with no undercuts, and finally with a digital caliper to make sure of all preparation dimensions (4 mm depth, 3 ± 0.2 mm mesiodistal width, 5 ± 0.2 mm buccopalatal width, 2 ± 0.2 mm circular axial wall thickness) *(Figure 4)*. At this stage, about standardized 2 mm layer of flowable composite resin material was preserved to the pulp chamber floor.[27,34]

A total of twenty endocrown restorations were constructed using the same CAD/CAM system used for the standardized endocrown tooth preparation. Designing phase for Group C endocrowns involved margin line defining with determination of cement gap thickness (50 µm)[3,29] with its distance from this margin (1 mm). For standardization of the endocrown morphology for all studied teeth, one model of maxillary first premolar teeth from the software library was chosen as a master reference model (alternative model selected) then was applied and auto-adapted for all prepared teeth. For more accuracy, the external dimensions of the finished master model on the first tooth were measured, saved, and then applied precisely with all other teeth *(Figure 5)*.

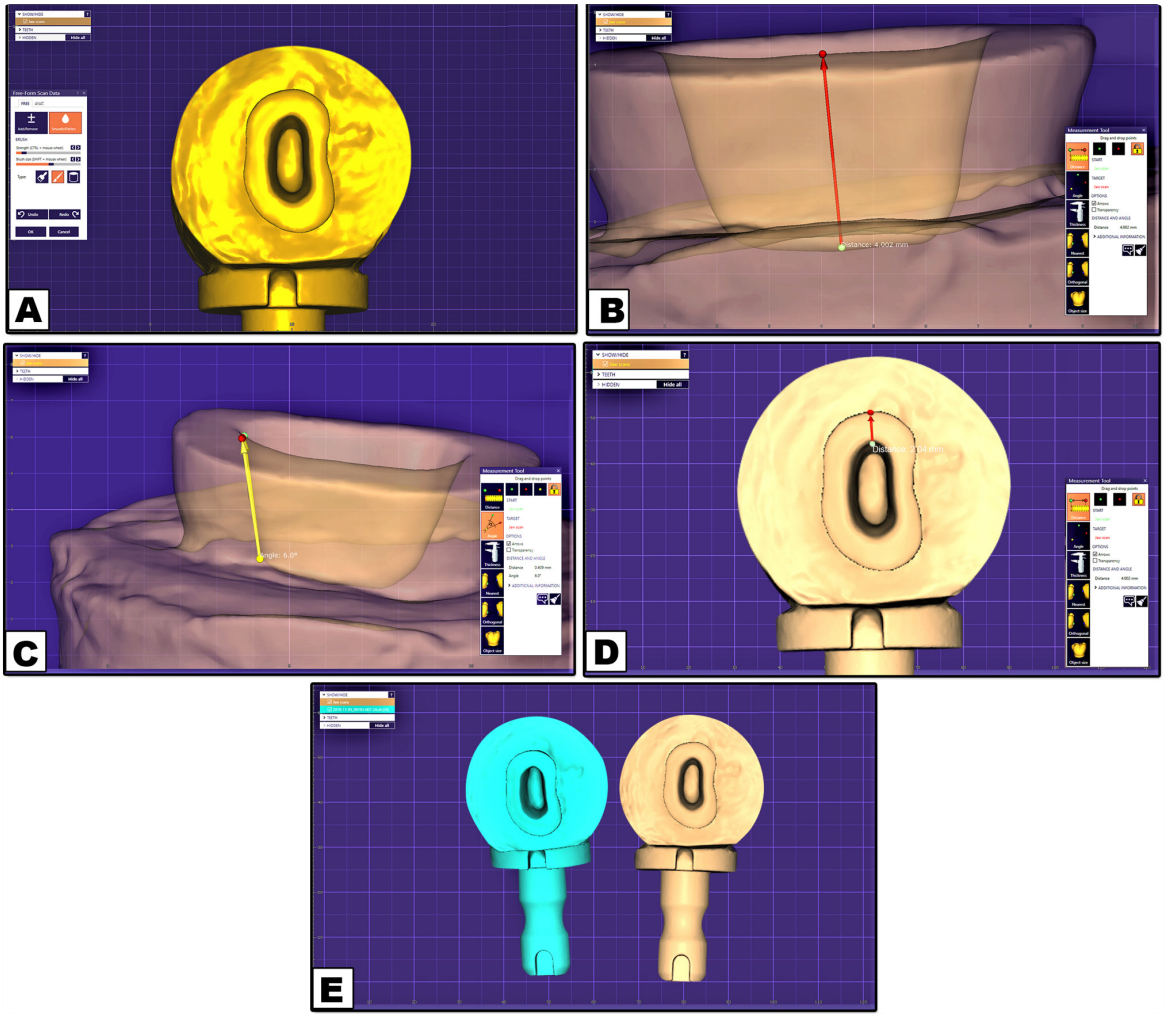

Figure 3: Designing phase for CAD/CAM endocrown tooth preparation; (A) smoothening and finishing of a circumferential butt margin, (B) maintaining a central cavity with a depth of 4 mm, (C) axial wall internal taper of 6°, (D) circular axial wall thickness of 2 ± 0.2 mm, and (E) pre- (left) and post- (right) designing comparison.

Designing phase for Group P endocrowns included two stages. The first stage for PEKK coping involved margin line defining (1 mm from the cavo-surface margin and parallel to it) with determination of cement gap thickness (50 µm) and its distance from this margin (zero mm). For standardization of the coping morphology for all studied teeth, the same 'alternative' master model with the same dimensions used for Group C was used. Then, according to the manufacturer's recommended instructions for IPS e.max CAD crown in the premolar region, the master model was uniformly reduced/shrank by 1.5 mm from all aspects with 6° axial occlusal convergence. The second stage for IPS e.max CAD veneering included determination of the margin line defining, cement gap thickness (50 µm), and its distance from the external cavo-surface margin (1 mm) using the same previously-used 'alternative' master model *(Figure 5)*.

The milling phase for Group C included 10 endocrowns that were wet-milled using 10 IPS e.max CAD blocks with diamond grinding tools (CORiTEC) used for glass ceramics. For Group P, 10 copings with their corresponding veneerings were milled. The copings were dry-milled using 1 Pekkton ivory milling blank with sharp single-bladed, slide-coated milling tools (CORiTEC). The veneerings were wet-milled using 10 IPS e.max CAD blocks with the same grinding tools used for Group C. After milling was completed and according to the manufacturer's instructions, the IPS e.max CAD crystallization and glazing processes were performed using a compatible ceramic furnace (Programat P500).

The assembly procedure for Group P endocrowns included surface treatment of both the coping and the veneering according to the manufacturer's instructions. The PEKK coping was firstly sandblasted from all aspects with unrecycled 110 µm aluminum oxide (Zeta Sand) at 2 bar (0.2 MPa) pressure for 5 seconds at a distance of 1 mm and at an angle of 45°. Then, it was cleaned well using steam and dried with oil-free air for 20 seconds.[20,35] After that, the only external surface to be assembled is wetted with a PMMA and composite primer (visio.link) that was polymerized immediately after its application with a suitable LED polymerization unit (Elipar DeepCure-S) for 40 seconds per surface.[20] According to the manufacturer's guidelines and instructions, the fitting surfaces of all IPS e.max CAD veneerings were treated with 9.5% hydrofluoric acid etching gel (Porcelain Etchant) for 90 seconds, rinsed off properly for 90 seconds and then thoroughly air-dried for 20

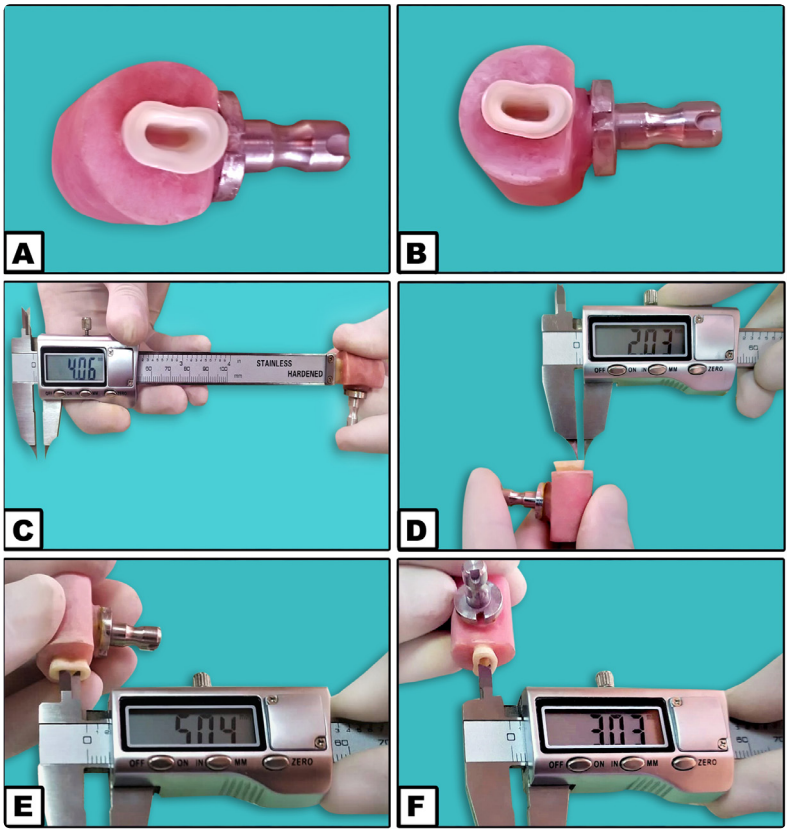

Figure 4: Evaluation of the endocrown preparation features; (A and B) visually and (C - F) with digital caliper: (C) depth, (D) circular axial wall thickness, (E) buccopalatal width, and (F) mesiodistal width.

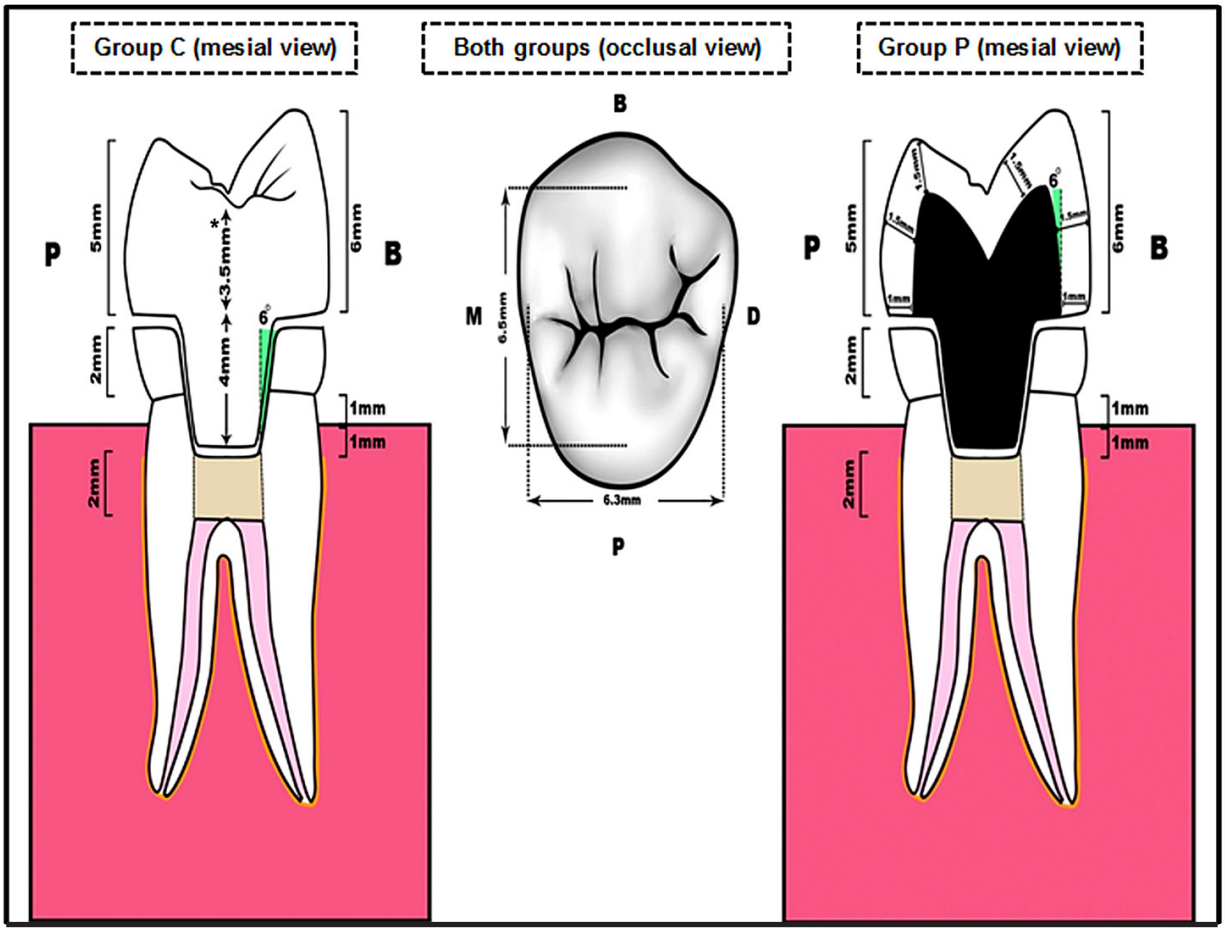

Figure 5: Schematic diagrams showing endocrown features of the master reference model selected and applied for all teeth specimens; mesial and occlusal views for both groups. The (*) refers to dimension distally = 3.2 mm.

seconds. After that, 2 thin coats of a silane coupling agent (Porcelain Primer) were applied for 30 seconds and then carefully air-blown for 5 seconds.[36] After surface treatment completed, a dual-cured, adhesive composite resin luting cement (Duo-Link Universal, Universal shade) was used to cement each veneering to its respective coping and assemble both parts. A specially-designed loading device was used to standardize the load (1kg) applied during assembly procedure.[9] The load was applied perpendicularly to the occlusal surface of the veneering and maintained for 30 seconds before light curing.[5,24]

For cementation of endocrown restorations, all 20 prepared teeth were etched using a 37% phosphoric acid etching gel (N-Etch Etching Gel) for 15 seconds, then properly water-rinsed and gently air-dried. Then, light-cured universal dental adhesive (All-Bond Universal) was applied and light-cured for 10 seconds. The same surface treatment and cementation protocol used during the assembly procedure for Group P endocrowns were followed here for final tooth cementation for both groups and through the same operator. Finally, post-cementation endocrown restorations for both groups were finished and polished at marginal cementation lines.[1,3,24,26,29,30]

After storage in distilled water at 37°C in an incubator for 24 hours, all cemented specimens were subjected to "artificial thermomechanical aging".[3,5,26,33] Using a thermal cycling apparatus (Thermo Scientific), all specimens were subjected to 10000 cycles altering between 5°C and 55°C with a dwell time of 30 seconds in each distilled water bath and 5 seconds of transfer time to resemble approximately one year of clinical service.[30,34,35] Then, using a chewing simulator machine (Chewing Simulator CS-4.4) simulating also one year of oral service, they were subjected to 240000 load cycles at a frequency of 1.6 Hz to replicate an intermittent unidirectional axial load of 50 N on each restoration. This load was applied with a 6 mm-diameter, steatite-ceramic, ball-shaped antagonist in the center of the occlusal surfaces contacting buccal and palatal cusps and parallel to the long axis of the teeth *(Figure 6)*. Throughout the test, the specimens were submersed into chambers containing distilled water.[3,10] After completion of all chewing cycles successfully, each specimen was eventually examined using a calibrated stereomicroscope (SZ61TR, Model SZ2-ILST) up to 10x magnification for a close, detailed survival evaluation before fracture resistance testing.[5,10]

After the fatigue testing, all surviving specimens were subjected to the fracture resistance testing using a universal testing machine (model 3365). The compressive load was axially and centrally applied with a load cell of 5kN force using a 6 mm-diameter, stainless steel ball-shaped loading piston at a cross-head speed of 0.5 mm/min until permanent deformation or failure.[3,5,9,22,27,30,33] The maximum load to produce a fracture was recorded in newton (N) using the Bluehill 3 testing software.

The fractured specimens were qualitatively evaluated using the previously-used calibrated stereomicroscope up to 40x magnification.[1,5,10,26] After the assessment of all specimens based on a 3-examiner agreement,[26] failure modes were specified and classified according to the description in Table 2.[10] Representative fractured specimens of each failure category for both groups were subjected to Scanning Electron Microscopy (SEM) (JSM.6510LV) and images of the fracture surfaces were taken and documented at different magnifications (up to 300000x) according to the region of interest. These scanning images were analyzed to determine the mode of failure based on systematic mapping of the fracture origin(s) and the overall direction of crack propagation for both studied groups.[5,10,26,32]

Figure 6: Dynamic Loading Testing; the specimen in its chewing simulator position with centralized axial loading.

The data were tabulated, coded then analyzed on the environment of IBM SPSS statistical software (version 22). The descriptive statistics for quantitative data were calculated in the form of mean ± standard deviation after testing normality using the Shapiro-Wilk test. Qualitative data were described using the number and percent. In the analytical statistics, the significance of difference was performed using three categories of tests; Student t-test, Monte Carlo test, and finally with One-way ANOVA test. The statistical significance of the obtained results was set at ≤ 0.05 level.

RESULTS

All tested specimens were survived after the artificial thermomechanical aging protocol without any detectable sign of early failure with a 100% survival rate for both groups. It was found that the mean failure load values for Group C and Group P were 1433.47 ± 174.39 N and 1831.37 ± 240.69 N, respectively. Student t-test showed that there was a statistically significant difference between tested groups ($p < 0.001$) that a significantly higher failure load was recorded for Group P. *(Table 3)*

Table 2. Classification of the failure modes.

Type	Failure mode	Description	Prognosis
I	Adhesive failure	Debonding of the restoration (endocrown or veneering) without fracture.	Non-catastrophic/ repairable/ favorable
II	Cohesive failure	Fracture of the restoration (endocrown or veneering) without displacement (no loss of adhesion).	
III	Cohesive-Adhesive failure	Fracture of the restoration (endocrown or veneering) with displacement (loss of adhesion).	
IV	Complex fracture above the CEJ	Fracture of the restoration (endocrown or veneering)/tooth complex above the CEJ.	
V	Complex fracture below the CEJ	Fracture of the restoration (endocrown or veneering)/tooth complex below the CEJ, which requires tooth extraction.	Catastrophic/ non-repairable / unfavorable

CEJ: cemento-enamel junction

Table 3. Comparison of mean failure load values (in newton) among tested groups using Student t-test (t) and comparison of their failure modes (with distribution) using Monte Carlo test (MC).

Group	Failure Load					Failure Mode							
						Favorable					Unfavorable		MC
	n	Mean	SD	t	P	I	II	III	IV	Total %	V	Total %	p
(C)	10	1433.47	174.39	4.23	< 0.001*	0	0	0	0	0%	10	100%	0.036*
(P)	10	1831.37	240.69			0	0	3	2	50%	5	50%	

***significance at p-value ≤ 0.05** **SD:** standard deviation

Stereomicroscopic analysis revealed that all tested specimens (n = 10) of the Group C showed only the unfavorable fracture pattern (100% type V) including the IPS e.max CAD endocrown/tooth complex below the CEJ. Different fracture paths were observed, however most fractured specimens were broken with a mesiodistal vertical fracture splitting the restoration into two main pieces. Most of these wedge-opening fractures progressed and advanced also within the tooth provoking severe root breakdowns as shown in (*Figure 7*). In Group P, only half of the tested specimens showed the unfavorable fracture pattern, while the other half expressed a type of favorable fracture. Only three specimens showed split fracture mesiodistally extending through all the restoration to the root. In addition, half of the fractures were only viewed through the IPS e.max CAD veneering not extending to the intact PEKK coping (*Figure 8*). Monte Carlo test illustrated a statistically significant difference between tested groups considering the failure mode (p = 0.036) as shown in Table 3. For Group P, One-way ANOVA test showed that the mean failure load value had no significant effect on the failure mode (p = 0.22) (*Table 4*). Consequently, only the endocrown restoration material had a significant effect on both the failure load and mode for both tested groups.

The fractographic analysis through Scanning Electron Microscopy (SEM) for all fractured restorations in Group C revealed that the fracture origin was always identified at the occlusal surface, basically from the main contact loading area underneath the loading ball of the fracture resistance test. Then, it was propagated corono-apically with the presence of hackle lines indicating the course and direction of crack propagation (DCP). Tooth fracture was illustrated with all scanned specimens of Group C (*Figure 9*). For Group P, all fractured specimens showed that the main origin of the fracture was located at the occlusal surface from the major contact loading area and propagated corono-apically. Additional secondary minor events (secondary origins) were noticed at the occlusal surface in some specimens. Both the veneering and coping had revealed fractured surfaces with hackle lines and arrest lines that indicated the direction of crack propagation. Diffused and well defined main arrest lines (MAL) with accompanied pronounced irregularities that are characteristic for polymers, accumulating high elastic energy before fracture, were identified through the coping fracture. The SEM images suggested that the fracture origins with the indicating below concave arrest lines were identified also at the assembly occlusal surface of the coping and this coping fracture propagated apically as well (*Figures 10 and 11*).

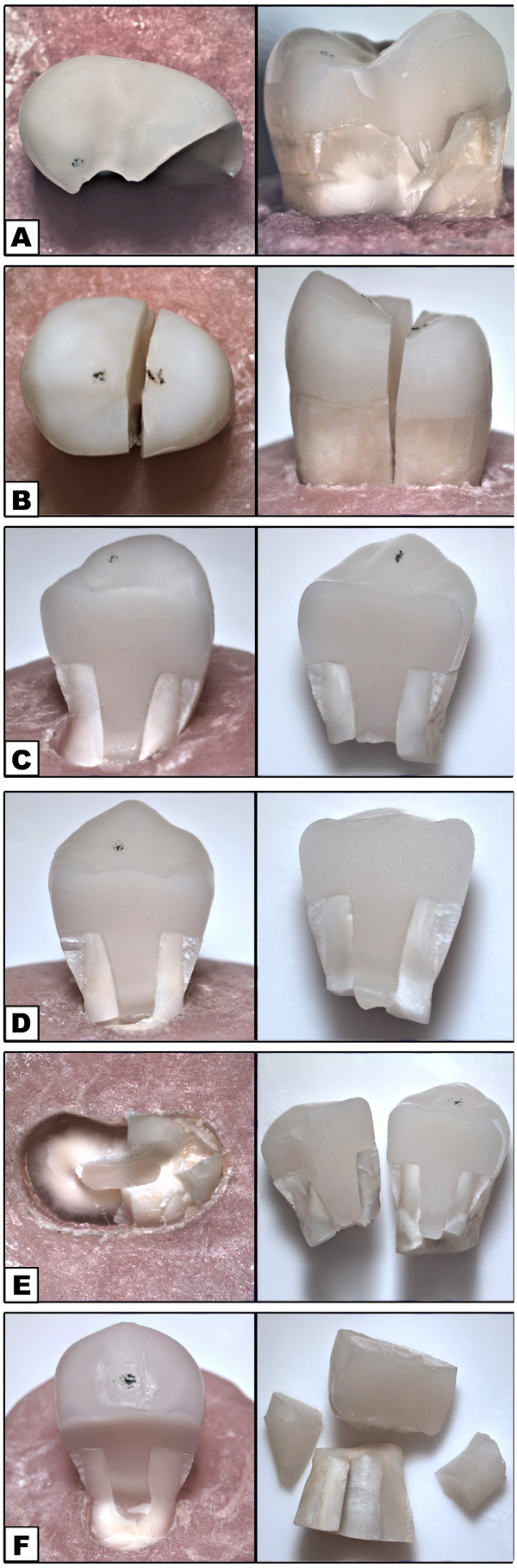

Figure 7: Representative stereomicroscopic images for failure mode assessment of Group C specimens; specimens (A-F) show only type V failure mode.

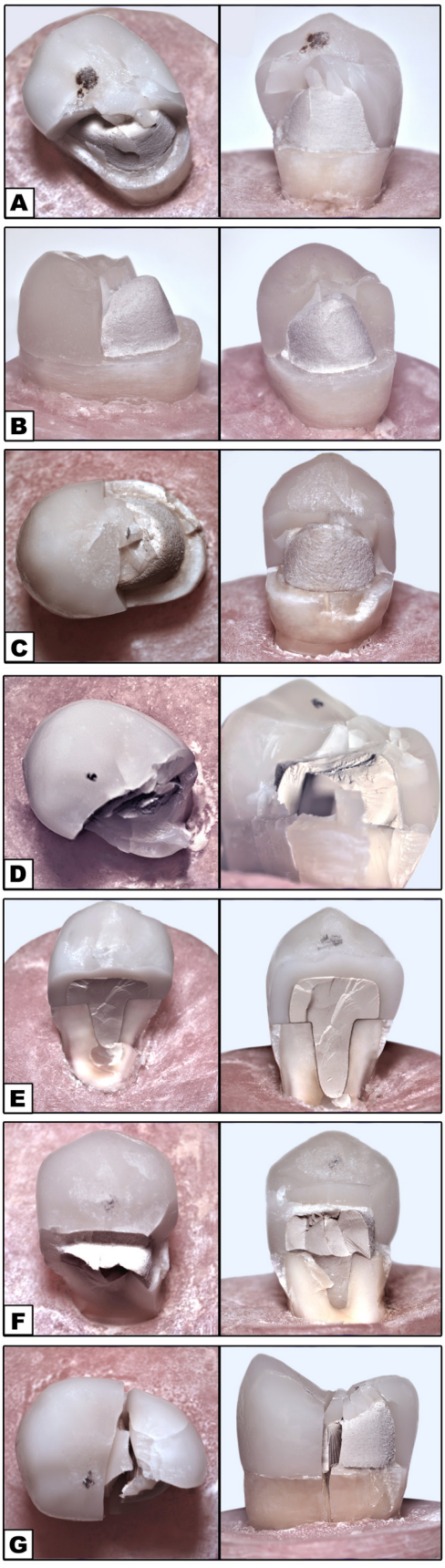

Figure 8: Representative stereomicroscopic images for failure mode assessment of Group P specimens; specimens (A and B) show type III failure mode, specimen (C) shows type IV failure mode, while specimens (D–G) show type V failure mode.

Table 4. Fracture load distribution according to fracture mode among Group P specimens with One-way ANOVA test (F).

Failure Mode	Failure Load			Test of Significance	
	n	Mean	SD	F	p
III	3	1931.72	222.51		
IV	2	1565.34	168.01	1.88	0.22
V	5	1877.56	230.07		

SD: standard deviation

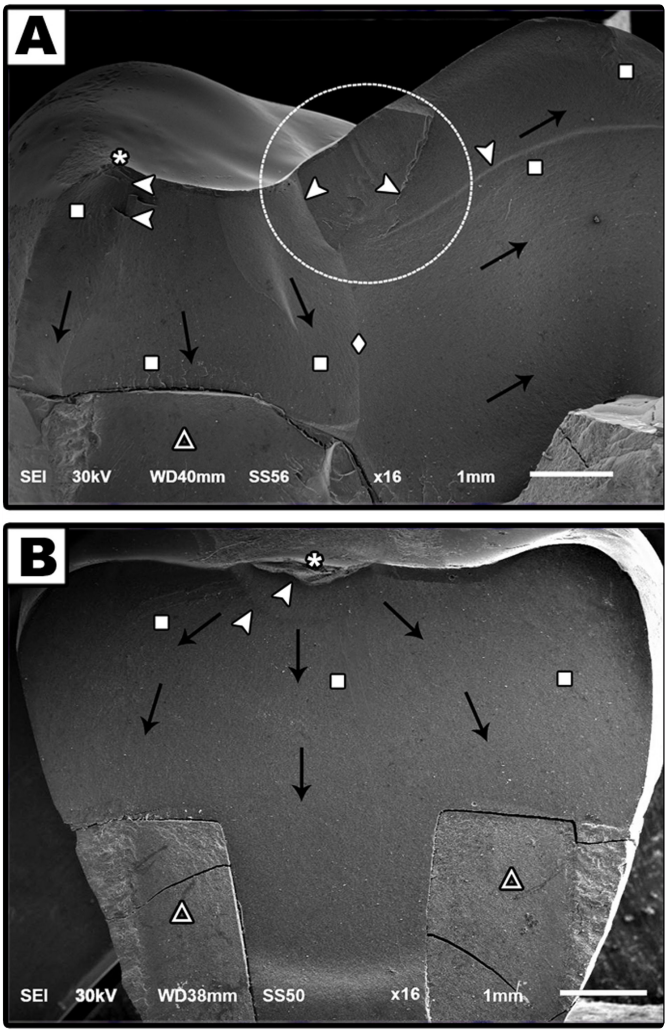

Figure 9: Representative SEM images (16x) for fractographic analysis of Group C fractured specimens (Type V failure mode); Asterix: The origin of the fracture at the occlusal surface loading area with the indicating below concave side of the first arrest line (arrowhead). Square: Hackle lines clearly visible indicating the direction of crack propagation (DCP, black arrow). Arrowhead: Arrest lines representing the limits of a small internal chip (Dotted circle). Diamond: Compression curl indicating the CP ends and begins in another direction before total fracture. Triangle: Fracture of the endocrown/tooth complex.

DISCUSSION

Rehabilitation of severely-damaged ETT proceeds to be a challenging issue in dental practice.[9] They are usually restored using the conventional post-retained restorations. Recently, CAD/CAM technology with the development of restorative materials and adhesive methods have made the conservative endocrowns constitute a reliable promising restorative approach.[34] Different CAD/CAM polymers have been presented with a PEKK-based polymer (Pekkton ivory) has been introduced as an alternative intra-radicular post-core material.[20] This PEKK material is considered an attractive novel material for endocrown systems especially with the fabrication versatility including pressing and milling. This study was conducted to assess the biomechanical behavior of a PEKK-based endocrown system through the *in-vitro* testing that is considered a prerequisite to any clinical investigation.[9]

The PEKK material was used in this study as coping material for endocrowns but veneered with stable IPS e.max CAD ceramic instead of the stainable weak commonly-used veneering composite resin. Amelya *et al.*[37] reported that FPDs fabricated from PEKK veneered with cemented lithium disilicate material had significantly higher fracture load compared to PEKK veneered with composite resin. IPS e.max CAD was used in this study being one of the most widespread restorative materials for single-unit crowns and endocrowns with long-term clinical success.[26,27]

In this study and for methodological homogeneity, all selected natural teeth were prepared according to the clinically-established preparation guidelines for endocrowns using a novel CAD/CAM technique to ensure standardization of all preparations. A standardized layer of flowable composite was applied to close the entrances and undercuts of buccal and palatal canals, to attain symmetrical flat pulp chamber floors roughly parallel to and at similar depths from the sectioned surfaces, and to enhance the bonding of endocrowns.[3,10,24,27,34]

The aim of this study was to investigate the mechanical performance and the fracture behavior of endocrowns fabricated using novel restorative material; hence, axial loading would be more recommended. Gresnigt *et al.*[30] showed that axial loading may assess more directly the impact of inherent properties (modulus of elasticity) and thickness of the restorative materials

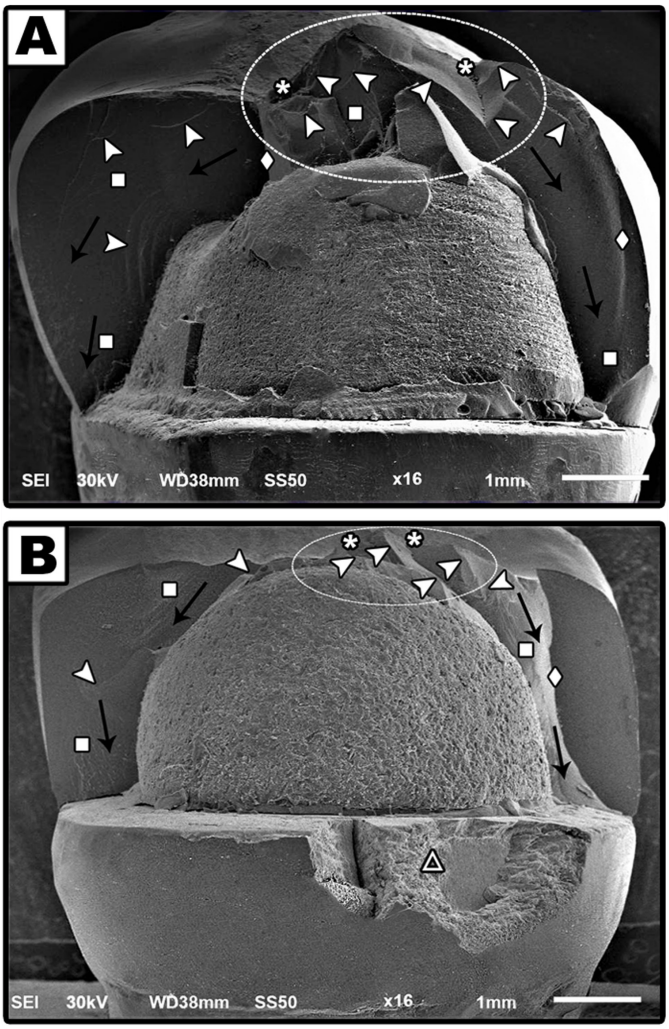

Figure 10: Representative SEM images (16x) for fractographic analysis of Group P fractured specimens including Type III (A) and Type IV (B) failure modes; Asterisk: Fracture origins at the loading occlusal surface of the veneering. Square: Hackle lines indicating the direction of crack propagation (DCP, black arrow). Diamond: Compression curls. Arrowhead: Diffused Arrest lines through the veneering. Dotted circle: Forking (multiple crack branching with high stresses). Triangle: Fracture of the veneering/tooth complex.

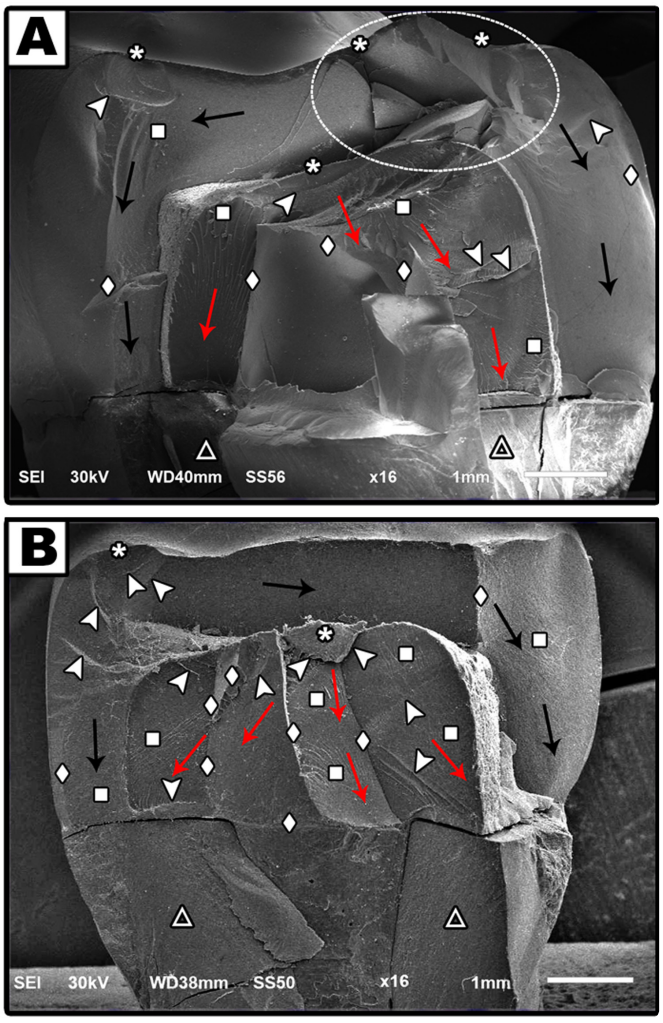

Figure 11: Representative SEM images (16x) for fractographic analysis of Group P fractured specimens (Type V failure mode); Asterisk: Fracture origins at the loading occlusal surface of the veneering and at the coping occlusal surface with the indicating below concave side of the first arrest line (arrowhead). Square: Hackle lines indicating the direction of crack propagation (DCP, the black arrow for veneering, and the red arrow for coping). Arrowhead (Arrest lines) and Diamond (Compression curls) are more diffused through coping than veneering. Dotted circle: Forking (multiple crack branching with high stresses). Triangle: Fracture of the endocrown (both parts)/tooth complex.

on their mechanical behavior instead of lateral loading, which would be more related to the adhesion influence of the restoration on the bonding outcome and retention.[22] All tested specimens were survived after the artificial thermomechanical aging protocol without any detectable sign of early failure. This result suggested that both groups can resist the repeated occlusal loads that teeth are normally exposed to during oral function The high survival rate of Group C specimens is in accordance with other limited studies[3,26,38] that also used IPS e.max CAD endocrowns for maxillary premolar teeth.

The results of the fracture resistance testing and fractography showed that the used novel endocrown system had a statistically significant positive effect on both failure load and mode. Accordingly, the main tested null hypothesis that the used novel endocrown system will improve the biomechanical performance within the tooth/restoration complex of the restored endodontically treated maxillary first premolars, was accepted.

Despite the statistically significant difference, the observed mean values of fracture loads for both examined groups at the time of fracture under axial loading (1433.47 ± 174.39 N for Group C and 1831.37 ± 240.69 N for Group P) were not only surpassed the biting force in the maxillary premolar region (normal = 450 N or during clenching = 660 N), but also exceeded the maximum human masticatory forces reported in the literature (900-1000 N in the first molar region with severe parafunctional bruxing habits).[39-41]

The 100% catastrophic fracture pattern of Group C specimens may be consistently in agreement with other studies where almost all tested specimens exhibited unfavorable fracture mode extending to the root.[3,26] Rocca *et al*.[26] explained that most IPS e.max CAD endocrowns were broken with a mesiodistal vertical fracture splitting the restoration and catastrophically progressed into the root because of the ceramic extension into the central cavity through the pulp chamber.

There has been no, or rather the authors are unaware of, similar study published in the dental literature concerning the using of such bilayered endocrown system as a reliable effective type of restorations for endodontically treated teeth, especially when such high performance polymer PEKK and ceramic materials are used as a coping and a veneering, respectively. This means no studies could be referenced for direct comparison with the results of the novel group tested. Moreover, the direct comparison of results obtained using other restorative techniques with ours to know the degree of compatibility/difference may be erroneous and improper because of the several variations in the study designs. The fracture strengths and failure modes of restorations including endocrowns can be influenced by many factors such as: using human or artificial teeth, tooth preparation guidelines, restoration shape, materials used, loading technique (axial or lateral, crosshead speed, ball diameter, etc.), artificial aging protocol, method of fabrication, and luting method. However, this comparison may indicate the validity of the tested novel endocrown system as favorable restoration for endodontically treated maxillary premolars taking into account both fracture load and mode.

Regarding the comparison with our results, it was found the most common fracture pattern in case of IPS e.max CAD crown retained with fiber post and core was fracture above the CEJ (60% repairable) and the fracture below the CEJ recorded 40% non-repairable at mean fracture load of 1301 N. Also, Cerasmart (hybrid nano-ceramic) endocrowns showed 70% repairable and 30% non-repairable fractures at 1522 N mean fracture load.[27] In case of monolithic translucent zirconia endocrowns, Hassouneh *et al*.,[42] recorded primarily catastrophic root failures occurred in a mesiodistal direction around the mid sagittal axis in the direction of the applied static load. In addition, the failure types were mainly cohesive failure in the endocrown material for the Cerec maxillary premolars endocrowns, while Vita Enamic (hybrid ceramic) endocrowns were characterized by cohesive failure in the enamel/dentin structure.[43] Resin nano-ceramic (Lava Ultimate) endocrowns for maxillary first premolars experienced non-repairable fractures predominantly with a mesiodistal vertical fracture splitting the restoration.[44] Also for endodontically treated maxillary premolars, the conventional composite resin produced 70% non-repairable fracture type while both bulk-fill restorative composite and ceramic inlay showed 50% repairable and 50% non-repairable fractures.[45] According to Luca *et al*.,[46] all the fractures in the premolars restored with a CAD/CAM composite endocrown (Brilliant Crios) occurred below the CEJ. Using cast onlay and inlay restorations luted with adhesive resin cement for endodontically treated maxillary premolars with MOD cavities often resulted in unfavorable failure mode.[47]

High fracture load values of the Group C specimens may be attributed to multiple factors. The fracture load values of glass ceramic endocrowns behaved as a function of the sample thickness, meaning that the fracture resistance of glass ceramic endocrowns increases with increasing occlusal thickness.[11] Besides, it could be expected that the greater the adhesion of the restoration, the better the stress distribution within the system and thus the higher fracture resistance.[27] A more conservative coronary preparation with a butt margin and minimal remaining height of 1.5 mm was recommended for adequate adhesion to retain this etchable endocrown.[34] Additionally, the fitting accuracy of restorations has been shown to affect and be crucial for the clinical long-term success of restorations. The butt margin design used in this study provides a configuration without the ferrule complexity or thin margins, minimizing the milling bur limitations in reproducing the intaglio surface of endocrowns and permitting the easy escape of resin cement, resulting in proper seating and internal fit of all endocrowns with minimal marginal gaps.[9,12]

The fracture resistance values of PEKK polymer-included endocrowns used in this study are significantly higher than monolithic glass ceramic specimens ($p < 0.001$), despite providing much higher flexural strength. Low flexural strength of the material does not always mean low fracture resistance (the flexural strength of PEKK is 200 MPa and for IPS e.max CAD is 344 MPa). Similar mechanical properties (compressive strength, modulus of elasticity and resilience) of this compliant polymer material (PEKK) to that of natural dentition improve the reliability of the restorative system via producing a better biomechanical match between tooth and restoration.[11,22] The compressive strength of PEKK material and tooth dentin is 246 MPa and 297 MPa, respectively, while the elastic modulus for both is 5.1 GPa for PEKK and 18.6 GPa for dentin. On the other side, the rigid IPS e.max CAD with high elastic modulus of 95 GPa is not sufficiently elastic to accompany the tooth natural flexural movements.[23,24]

The higher values of fracture loads for Group P specimens may be related to the accurate manufacturing of PEKK material with better marginal adaptation and internal fit when compared with the glass ceramic material. The coping material is milled in its final form without further processing steps that may be accompanied by dimensional changes. With the IPS e.max CAD, shrinkage during the sintering process appears to have a negative impact during production of dental prostheses.[48,49] In addition, resin-based materials with such a polymer matrix may provide better marginal accuracy during milling of thinner structures due to better CAM machinability and thus restoration margin/edge stability. In contrast, the brittleness of the glass matrix of ceramic materials may lead to easy breaking out of ceramic crystallites with the pressure

of milling instruments.[50] According to Park *et al.*,[48] Pekkton crown exhibited lower gap values and better fit in all regions than IPS e.max CAD. Also, Bae *et al.*[49] observed excellent marginal and internal fits for PEKK copings.

With high elastic modulus mismatch between two cemented components, the flexible PEKK coping (5.1 GPa elastic modulus) induced lower internal stresses with more favored uniform distribution, but rather more stresses were transferred to the adjacent interfacial cement and the rigid IPS e.max CAD veneering (95 GPa elastic modulus) leading to more favorable fracture patterns.[20,51] That's why half of the bi-layered restoration fractures were only viewed through the IPS e.max CAD veneering and not extending to the intact PEKK coping with few root fractures.

The uniaxial loading applied in this study could be one of the main reasons that explain absence of complete endocrown or only complete veneering debonding (type I adhesive failure mode), in addition to the quality of adhesive cementation procedure and tooth/coping preparation guidelines. The endocrown/crown preparation with smaller axial wall divergence/convergence (6°) provides a better internal fit and significantly smaller internal gaps that more parallel surfaces are easy in milling. This can be explained by that the closer the restoration geometry to the milling burs geometry, the better the resulting internal fit.[28]

SEM fractographic analysis for both groups showed that all fractures mainly originated at the loading contact point with corono-apical direction of crack propagation. Secondary origins were identified at the occlusal surface in some specimens especially of the Group P. This can be further explained by Finite Element Analysis (FEA) data for stress distribution assessment.[5,32] Also, this FEA study may be combined with Weibull Analysis to interpret why failure load value had no significant effect on the resultant failure mode.

A limitation of the current research is the geometry of the load application that only axial direction and not sliding was tested. In fact, such applied axial forces are always accompanied by lateral forces during oral function.[30] Thus, future studies should focus on the behavior of such tested endocrowns using different tooth preparation guidelines, and under dynamic loading both axially and laterally before prospective long-term clinical studies are commenced, confirming or negating the results of this study.

CONCLUSIONS

Under the conditions of this *in-vitro* study, it was concluded that the tested novel endocrown system (PEKK veneered with cemented IPS e.max CAD) improved the biomechanical behavior of the tooth/restoration complex in the restored severely-destructed endodontically treated maxillary first premolar teeth, with a significant positive effect on both failure load and mode in comparison to the conventional monolithic IPS e.max CAD endocrowns.

MANUFACTURERS' DETAILS

- IsoMet 4000: BUEHLER, IL, USA.
- Race/25 mm: FKG Dentaire SA, La Chaux-de-Fonds, Switzerland.
- Nexcomp Flow A3: META BIOMED CO., LTD, Chungcheongbuk-do, Korea.
- All-Bond Universal: Bisco Inc., IL, USA.
- Elipar DeepCure-S: 3M ESPE Dental, MN, USA.
- Milling unit BF 2: Bredent GmbH & Co.KG, Senden, Germany.
- Harmony light fast setting: ELSODENT, Île-de-France, France.
- IPS e.max CAD: Ivoclar Vivadent, Schaan, Liechtenstein.
- Pekkton ivory: Cendres+Metaux SA, Biel/Bienne, Switzerland.
- Identica hybrid: Medit dental, Seoul, Korea.
- D-SCAN Scanspray: Dentify GmbH, Engen, Germany.
- colLab Scan: Medit dental, Seoul, Korea.
- DentalDB 2.2 Valletta: exocad GmbH, Darmstadt, Germany.
- MillBox: CIMsystem, MI, Italy.
- SUM3D Dental: CIMsystem, MI, Italy.
- CORiTEC 250i touch: imes-icore GmbH, Eiterfeld, Germany.
- CORiTEC: imes-icore GmbH, Eiterfeld, Germany.
- Programat P500: Ivoclar Vivadent, Schaan, Liechtenstein.
- Zeta Sand: Zhermack S.p.A., RO, Italy.
- visio.link: Bredent GmbH & Co.KG, Senden, Germany.
- Porcelain Etchant: Bisco Inc., IL, USA.
- Porcelain Primer: Bisco Inc., IL, USA.
- Duo-Link Universal: Bisco Inc., IL, USA.
- N-Etch Etching Gel: Ivoclar Vivadent, Schaan, Liechtenstein.
- Thermo Scientific: Thermo Fisher Scientific Inc., MA, USA.
- Chewing Simulator CS-4.4: SD Mechatronik, Feldkirchen-Westerham, Germany.
- SZ61TR: Olympus Co., Tokyo, Japan.
- Bluehill 3 testing software: Instron Industrial Products, MA, USA.
- Universal testing machine: Instron Industrial Products, MA, USA.
- JSM.6510LV: JEOL Ltd., Tokyo, Japan.
- IBM SPSS statistical software version 22: IBM Co., NY, USA.

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