Fracture resistance of maxillary premolars restored with different endocrown designs and materials after artificial ageing

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Abstract

Purpose: To evaluate the effect of three different designs and two monolithic ceramic materials on the durability and fracture resistance of endocrowns on maxillary first premolars, in comparison to post-and-core crowns.

Methods: Fifty-six maxillary premolars were endodontically treated and shortened to a level of 2 mm from the cervical line, and randomly categorized into six endocrown groups and post-and-core crown control group (n=8); E1: endocrowns with flat occlusal table (without ferrule), E2: endocrowns with 1.5 mm circumferential ferrule, E3: endocrowns with 1.5 mm buccal ferrule preparation. Two materials were used for endocrowns: zirconia (4YSZ; Z), and lithium disilicate (L). The control group was restored with zirconia posts, and lithium disilicate crowns. All restorations were bonded using Panavia V5 and its respective primers and underwent thermo-mechanical fatigue with a 10 kg dynamic load for 1,200,000 cycles and thermocycling between 5 and 55 °C. Thereafter all survived specimens were loaded to fracture. The results were statistically analyzed using ANOVA and T-Test.

Results: None of the specimens showed any signs of debonding or fracture caused by the fatigue test. The PC control group showed no statistically significant difference in comparison to groups ZE1, ZE2 and LE2 (p > 0.05). However, it was significantly different from groups LE1, LE3, and ZE3 (p ≤ 0.05).

Conclusions: Preparation designs and materials affected the fracture resistance of endocrowns. The results showed a superiority of the post-and-core crowns, zirconia/lithium disilicate endocrowns with 1.5 mm circumferential ferrule, and zirconia endocrowns with the flat occlusal table.

Keywords: Endocrowns, Post-and-core crowns, Zirconia, Lithium disilicate

I. Introduction

Different treatment modalities and materials can be used for the final restoration of endodontically treated teeth. The development of adhesives enables restoration with less relying on macro-mechanical retention [1]. With sufficient surface area for adhesion, the need for the post-and core to support crowns is remarkably reduced [2]. Hence, posts are only indicated when other conservative treatment modalities are not reliable [3, 4]. The remaining tooth structure and the available adhesive surface area are the most important factors affecting the decision-making and the long term success of the final restorations of endodontically treated teeth [4, 5].

Gaining the advantages of conservation of tooth structure and adhesive dentistry, all-ceramic crowns with a coherent core inserted in the pulp access cavity (Endocrown) were introduced in 1995 by Pissi as a substitute to post-and-core crown treatment modality [6]. The endocrown technique was further developed by Bindl and Mörmann in 1999, the authors examined 19 endocrowns in 13 patients. After an observation period of two years, they concluded that the endocrown concept appears clinically feasible [7]. In a successive study, Bindl et al. [8] evaluated the survival rate of endocrowns for premolars and molars, after a mean observation period of 55 months. In comparison to conventional crowns with full and reduced height, the results showed that endocrown preparations were acceptable for molars, but appeared to be inadequate for premolars.

Laboratory studies on molar endocrowns revealed high fracture resistance [9-13]. Likewise, single-rooted mandibular first premolar endocrowns showed high fracture resistance compared to post-and-core crowns [14]. However, another study did not find any advantage of using endocrowns for single-rooted mandibular premolars in comparison to post-and-core crowns and concluded that both endocrowns and post-and-core crowns cannot rehabilitate endodontically treated premolars perfectly as sound teeth [15].

In terms of restorative materials, the appreciable mechanical properties of zirconia-based ceramics and lithium disilicate glass-ceramics make them the materials of choice for modern fixed prosthodontics [16]. Most of the clinicians have been selecting zirconia as a high strength ceramic, due to its superior mechanical properties, with the assumption that zirconia could reduce the risk of clinical failure [17]. While others prefer lithium disilicate ceramic, regarding its moderate flexural strength and modulus of elasticity in comparison to zirconia, predicting that the occlusal load would be transferred much better to the underlying luting agent and dentin surface. [18, 19]. Moreover, a study compared the behaviour of different materials for molar endocrowns under lateral and axial loading, exhibited no statistical difference in terms of fracture strength of different materials under axial loading, while lithium disilicate showed higher fracture resistance than multiphase resin composite endocrowns under lateral loading [20].

The surface area for adhesion, as well as the restorative materials,
seems to play a major role in the success rate of the final restoration of endodontically treated teeth [5]. This may contribute to the reportedly low survival rate of endocrowns in premolars than those used to restore molars [8, 18, 21]. Therefore, the current study aims to evaluate the fracture resistance and the failure mode of different endocrowns designs for maxillary premolars after thermomechanical loading, using 4-nmol/sytria-stabilized zirconia ceramic (4YTSZ) and lithium disilicate based glass-ceramic.

2. Materials and methods

Fifty-six human maxillary first premolars (free of caries) were selected out of 161 human maxillary premolars recently extracted for orthodontic purposes. The teeth were collected with informed consent from the patients, that those teeth would be used for research purposes. The teeth were stored in 0.1% thymol solution (Fagron GmbH, Barsbüttel, Germany) at 5 °C for two weeks and then moved to a distilled water container at 5 °C. The teeth were measured with a digital caliper, and the selected ones measured 9.1 ± 0.2 mm buccolingually and 6.9 ± 0.2 mm mesiodistally at the height of contour, at the cervix, the teeth measured 8 ± 0.3 mm buccolingually and 4.7 ± 0.3 mm mesiodistally. Moreover, the teeth with two pulp canals and similar root anatomy were included in the study. The teeth were randomly allocated into seven groups according to the preparation designs (flat occlusal table, 1.5 mm circumferential ferrule, and 1.5 mm buccal ferrule preparation) and materials used (zirconia-based ceramic (4YTSZ) and lithium disilicate glass-ceramic), the seven groups were given the following abbreviations; 1- zirconia endocrowns with flat occlusal table (ZE1); 2- zirconia endocrowns with 1.5 mm circumferential ferrule preparation (ZE2); 3- zirconia endocrowns with ferrule preparation at the buccal surface only (ZE3); 4- lithium disilicate endocrowns with a flat occlusal table (LE1); 5- lithium disilicate with 1.5 mm circumferential ferrule preparation (LE2); 6- lithium disilicate with 1.5 buccal ferrule preparation (LE3); and 7- post-and-core crown control group (PC), using ready-made zirconia post with composite buildup core and lithium disilicate crown.

2.1. Endodontic treatment (Groups: 1-7)

Endodontic access cavities were prepared using round, medium grit, diamond bur, and endodontic access burs (801.314.012, 014 and 383.314.010; Komet Dental, Lemgo, Germany). The canals were debrided to ISO size 35 (S.S. K-files; Komet Dental). A lateral condensation technique was used for obturation with sealer (AH. Plus; Dentsply, Constance, Germany) and gutta-percha (Roeko, Coltene Waledent, Schaan, Liechtenstein). Three subgroups (ZE1, ZE2, and ZE3) were milled out of pre-sintered zirconia discs (Katana STML zirconia-based ceramic (4YSZ), Kuraray), followed by a lithium disilicate crown. The palatal canals were prepared to a depth of 2 mm using tapered flat-ended diamond bur (Komet diamond conical 6845KR.314.016, 5p, Komet Dental). The pulpal inlay width was marked on the occlusal surface before preparation, to follow after reaching the desired depth with the secured parallelogram meter. The teeth for endocrowns without ferrules received no further preparation (groups: ZE1 and LE1).

The axial surface preparation was accomplished by using a guided round-ended tapered diamond bur (8856P.314.018, Komet Dental), a circumferential ferrule of 1.5 mm height and chamfer margin was prepared for the second design groups (ZE2 and LE2). The third endocrown design (ZE3 and LE3) was with a flat occlusal table and 1.5 mm ferrule preparation restricted to the buccal surface only (Fig. 1). The internal and external axial walls divergence were 2 and 3 degrees respectively, giving a total sum of 5-degree divergence corresponding to the angles of the diamond burs. The preparation dimensions were checked repeatedly during and after the preparation with a digital caliper till reaching the required dimensions, within a limit of ± 0.1 mm deviation.

2.2. Tooth preparation for the control group with post-and-core crowns (PC)

Control group specimens were prepared to receive a ready-made zirconia post (ER Kit 4441.000, Komet Dental) with a composite resin core followed by a lithium disilicate crown. The palatal canals were prepared up to size 70 with a length of 9 mm from the coronal flat surface. The ferrule preparation and the coronal chambers were prepared with the same parameters as endocrowns in groups ZE2 and LE2.

The zirconia posts were air-abraded with 50 µm alumina particles (Plurakorund; Pluradent, Offenbach, Germany) at 0.1 MPa pressure. The pretreated posts were ultrasonically cleaned (Sonorex super RK 510 H; Bandelin, Berlin, Germany) for 3 minutes with 99% isopropanol (2-Propanol; Otto Fischar GmbH, Saarbrücken, Germany). Ceramic primer plus (CLEARFIL, Kuraray) was applied to the posts surfaces and the tooth primer (Panavia V5 tooth primer, Kuraray) was applied to the cleaned and dried canals and the dentin surfaces using a small brush. The posts were then cemented to the canals with the luting resin (Panaviz V5, Kuraray) and the excess resin was spread over the coronal base and post head, then light-cured with a 440-480 nm light-curing hand-unit (Radii-cal; SDI, Victoria, Australia) for 20 seconds. The core was built up from a composite material (Clearfil core, Kuraray) and the abutment tooth was prepared to its final shape after 6 minutes. The core dimensions were 6.5 mm for the bucco-lingual width, 4.5 mm for the mesiodistal width, and 4 mm for the occluso-cervical height at the cusps and 2.5 mm at the central fossa.

2.3. Fabrication of the restorations

Impressions were taken with polyether impression material (Impregum, Penta H and L, Duosoft; 3M Espe, Neuss, Germany), using a double-mix dual-phase impression technique, and poured with type IV dental stone (Fujicrox; GC Corporation, Alisp, USA).

The stone dies were scanned using a laboratory scanner (D900L scanner; 3 Shape, Copenhagen, Denmark) and the design of the endocrowns/crowns was manipulated with the dental digital designer (Dental Designer, version 17.2.1; 3 Shape, Copenhagen, Denmark). The endocrown height from the occlusal table was 6 mm and 5.5 mm to the buccal and palatal cusps tips, respectively. The occlusal and axial crown thickness for the PC group was 1.5 - 2 mm and 1.2 - 1.5 mm, respectively. The medial surfaces of the buccal and palatal cusps were modified to acquire 30° angle slopes to the horizontal axis of the teeth (Fig. 1).

Three subgroups (ZE1, ZE2, and ZE3) were milled out of pre-sintered zirconia discs (Katana STML zirconia-based ceramic (4YTSZ), Kuraray), using a dental milling machine (ZENOTECH Select hybrid; WIELAND Dental, Pforzheim, Germany). The other three subgroups (LE1, LE2, and LE3) and the crowns for post and core control group were milled out of lithium disilicate glass-ceramic blocks (IPS e.max CAD; Ivoclar Vivadent, Schaan, Liechtenstein).
2.4. Luting procedure

The zirconia endocrowns were air-abraded with 50 µm alumina particles (Plurakorund; Pluradent) at 0.1 MPa pressure and cleaned in 99 % isopropanol alcohol. The lithium disilicate endocrowns were etched with 5% hydrofluoric acid gel for 20 seconds (IPS Ceramic Etching Gel; Ivoclar Vivadent), then washed with water followed by water/air spray into a diluted solution containing sodium carbonate powder before being dispersed following the manufacturer safety measures. Ceramic primer (Clearfil Ceramic Primer Plus; Kuraray) was used for the priming of fitting surfaces of both used ceramic materials for endocrowns.

The prepared teeth surfaces were cleaned with a rotary brush and fluoride-free pumice. The outer enamel surfaces of the prepared teeth were selectively etched with 37% phosphoric acid for 30 seconds (K-Etchant Gel; Kuraray). Tooth primer was applied to the prepared teeth surfaces for 20 seconds. Panavia V5 luting resin was applied and the cemented specimens held under constant pressure with a standardized force of 50 N. The excess resin was removed and the luting material was cured using light-curing unit (Radii-cal; SDI, Victoria, Australia) with a peak light intensity of 1200 mW/cm². All specimens were inspected under an optical microscope (Wild M420; Wild Heerbrugg, Gais, Switzerland) with 25× magnification to detect any changes in the structure of the tooth/cement/tooth interfaces. There were no signs of chipping or fracture of the cement/teeth interfaces. All specimens showed no signs of debonding or alteration of endocrowns/cement/teeth interfaces.

All specimens survived the thermomechanical fatigue test. In general, specimens showed no signs of debonding or alteration of endocrowns/cement/teeth interfaces. There were no signs of chipping or fracture of the teeth or the restorations (Fig. 2).

2.5. Dynamic loading and fracture load test

Using a dual-axis chewing simulation machine (Chewing Simulator; SD Mechatronik, Feldkirchen-Westernham, Germany); all specimens of all groups were subjected to 1.2 million mechanical chewing cycles with simultaneous thermocycling between 5 and 55 °C in distilled water with a 30 sec dwell time at each temperature with a total of 5,500 thermal cycles at a loading cycle frequency of 2.4 Hz. Steatite ceramic balls with a 6 mm diameter (Hoechst Ceram Tec, Wunsiedel, Germany) were used as antagonists to simulate the opposing teeth. Following a previous study protocol [10, 22], a vertical load of 98 N (10 kg) was applied with a 6 mm diameter round-ended stainless steel stylus to apply a quasistatic load on the same loading point of the chewing simulation, at 150° angle to the long axis of the teeth and 90° angle to the occlusal ridge of the buccal cusp with a crosshead speed of 0.5 mm/min (Fig. 1). The load required for the failure to occur was recorded and analyzed accordingly using the test controlling software (testXpert Software; Zwick).

2.6. Evaluation of the failure mode

After failure, all specimens underwent a stereoscopic evaluation using a light microscope 25× (Wild M420) to assess the modes of failure. According to the fracture line location, the modes of failure of the specimens were categorized into favourable and non-favourable failures. Favourable failures fracture lines located occlusal to the CEJ (restorable), while the non-favourable failure fracture lines located apical to CEJ (non-restorable).

2.7. Statistical analysis

The distribution of the data was explored using the Shapiro-Wilk test. The comparison of the mean values for the endocrown groups and the post-and-core crown control group were statistically analyzed with the Student's T-test. While comparisons between the endocrown groups were made using two-way analysis of variance (ANOVA). When two-way ANOVA showed an interaction, further analysis was made with one way ANOVA followed by Tukey HSD post hoc test for multiple comparisons. The modes of failure were analyzed with Chi-square test. The results were considered statistically significant if the p-value was equal to or less than 0.05, and non-significant if the p-value was more than 0.05. Statistical analysis was accomplished by using statistical software (IBM SPSS Statistics v20.0; IBM Corp).

3. Results

3.1. Fatigue test results

All specimens survived the thermomechanical fatigue test. In general, specimens showed no signs of debonding or alteration of endocrowns/cement/teeth interfaces. There were no signs of chipping or fracture of the teeth or the restorations (Fig. 2).
3.2. Fracture test results

The Shapiro-Wilk test of normality showed no statistical significance (p>0.05). Hence, the group’s fracture test results were normally distributed. The results revealed a statistically significant effect of different designs when using the same material, for zirconia and lithium disilicate (both p≤0.001). While the effect of using different materials with the same design groups was dependent on the design used. For the first endocrown design with a flat occlusal table; the mean fracture strength of zirconia ZE1 (1391 ± 309 N) and lithium disilicate LE1 (870 ± 167 N) showed a high statistically significant difference (p=0.001). The third design with a buccal ferrule revealed a statistically significant high fracture strength of zirconia (ZE3: 857 ± 136 N) when compared to lithium disilicate (LE3: 661 ± 143 N, p = 0.017). However, there was no statistically significant difference (p=0.539) in the mean fracture strength of the second design between zirconia (ZE2: 1165 ± 200 N) and lithium disilicate (LE2: 1225 ± 172 N).

The mean fracture strength values of comparison of the endocrowns to the post-and-core-crown control group were analysed with the student T-test. The mean value of PC (1440 ± 316 N) revealed no significant statistical difference (p=0.671, 0.064 and 0.121) to the groups ZE1, ZE2, and LE2 respectively. However a significant difference was observed (p≤0.001) to the groups ZE3, LE1, and LE3 (Table 1, Fig. 3).

3.3. Failure mode

The results revealed only two post-and-core crown specimens (25%) with a favourable failure mode. All other specimens of the test groups showed unfavourable failure modes (Table 2 and Fig. 4).

4. Discussion

The present study evaluated the fracture strength and mode of failure of three different endocrown designs for maxillary premolars, using two different monolithic ceramic materials, after thermomechanical loading. The physiological chewing forces are about 50 N. Therefore, 50 N loading has been applied in many laboratory studies for chewing simulation [26, 27]. In the present study, the applied load was doubled to 98 N, so that the specimens were placed under even more severe conditions, which may be more suitable to test the durability of posterior restorations, and that coincided with the estimated fatigue load of monolithic ceramics [28]. The average human chewing cycles were estimated to be 20,000 cycles for each month, which means 1,200,000 cycles for 5 years of clinical service of the restorations [29].

Because of the lingual inclination of teeth in centric occlusion and working bite (lateral relationship) [30], the occlusal force direction at centric occlusion tends to be buccal for maxillary and lingual for mandibular teeth [31]. In the laboratory studies, the load applied axially following the tripodization concept, in which exaggerated values and extraordinary failure modes encountered [9, 10, 22]. To imitate the harmful indirect impact effect and the lateral excursive forces on the working side during dynamic occlusion, the load applied laterally or obliquely on the buccal ridge of the buccal cusp of mandibular posterior teeth [13, 20], and on the median ridge of the buccal cusp of maxillary first premolar, which seems a reasonable position for the laboratory dynamic [22] and static load simulation [23-25].

With the development of adhesion techniques and materials, it has been clinically feasible to restore endodontically treated teeth without using extra radicular retentive means. Different studies on endocrowns reported excellent clinical results for molars, but the failure rate was relatively

### Table 1. Mean and standard deviation of fracture strength of the test groups given in Newton.

<table>
<thead>
<tr>
<th>Material</th>
<th>Design E1</th>
<th>Design E2</th>
<th>Design E3</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium disilicate</td>
<td>870 ± 167</td>
<td>1225 ± 172</td>
<td>661 ± 143</td>
<td>1440 ± 316</td>
</tr>
<tr>
<td>Zirconia</td>
<td>1391 ± 309</td>
<td>1165 ± 200</td>
<td>857 ± 136</td>
<td>857 ± 143</td>
</tr>
</tbody>
</table>

Statistically different means (p<0.05) within a row are indicated by different superscript upper case letters. Statistically different means (p<0.05) within a column are indicated by different subscript lower case letters. An asterisk indicates a statistically significant difference (p<0.05) to the post-and-core crown group.
high for premolars. So, using the endocrowns as a mode of treatment was recommended by previous studies to be limited to molars [7, 8, 18, 21]. In general, restored premolars are more likely to fail than restored molars [23]. This might be related to the fact that premolars have a limited surface area for adhesion, which might cause more strain and earlier debonding and/or fracture [7]. In this study, the adhesion surface in some groups was increased by extending the endocrown coverage to the external axial surfaces. Moreover, the pulpal inlay depth was increased by utilizing a part of the pulp chamber (2 mm) for more retention. Increasing the pulpal inlay depth further to the root was avoided, as utilizing part of the root for retention would not coincide with the endocrown concept [6, 7]. In a matter of fact, the adhesive bonding to the coronal dentine is stronger than bonding the root canal dentine [32]. Increasing the depth of a relatively small orifice pulpal inlay for premolars is not like molars, as many discrepancies would have been encountered during the digital workflow, which was also reported by other studies even for molars [33]. Moreover, a laboratory study found no significant difference in the fracture strength [34] and the survival rate [22] of 2 and 4 mm depth endocrowns, though the flat overlays with no pulpal retentive mean resulted in an inferior outcome [22].

Dental manufacturers continually develop improved restorative materials to overcome destructive oral challenges. Two monolithic dental ceramics were used in this study to evaluate which material is much more favourable in terms of fracture strength and mode of failure for endocrown applications. The first material was multilayer translucent zirconia (4YSZ) from the fourth generation of zirconia with an average flexural strength of 750 MPa, and the second one was lithium disilicate glass-ceramic with an average flexural strength of 530 MPa, according to the manufacturers’ data. Glass-ceramics possess some advantages over other ceramic materials, including the advantage of biomimicry, as its wear coefficient and aesthetic values are close to that of the natural tooth [16]. Further, the fourth generation of zirconia presents an auspicious combination of good mechanical and optical properties [35]. Hence, tooth morphology [36], the restoration design and thickness [37], as well as the microstructure of the restorative material [38] are affecting the survivability and fracture strength of restorative materials and the abutment tooth itself.

It has been recommended to avoid post placement in the maxillary first premolar, and if necessary to be limited to the palatal root canal [39, 40]. Clinically, both ready and custom made posts possess successful outcomes [41]. The post materials were formerly believed to have a direct impact on the teeth mechanical behaviour and mode of failure. The recent studies reported that the post materials showed no influence on the fracture strength [42] nor the mode of failure [43]. Nowadays, the most important factors are the ferrule presence [44] and the post bonding condition [45]. In a previous study, zirconia posts were recommended regarding their durable bond after ageing [46] and their favourable long-term clinical outcome [47]. Moreover, a very recent study found that the placement of crown increases the fracture strength of premolars regardless of the post or crown material used, especially under oblique load [48].

The restorations surface pre-treatment involved in the current study were based upon recommendations from previous studies [16]. The selective acid

| Table 2. Chi-square test of the failure mode given in percentage. |
|--------------------------|------------------|------------------|------------------|------------------|
| Material                  | Group            | Favourable       | Unfavourable     |                  |
|                          |                  | Restoration Fracture | Crown and root fracture | Restoration, crown and root fracture | Root fracture |
| Zirconia                 | ZE1              | 0.0%             | 12.5%            | 25.0%            | 62.5%            |
|                          | ZE2              | 0.0%             | 0.0%             | 0.0%             | 26.1%            |
|                          | ZE3              | 0.0%             | 62.5%            | 0.0%             | 8.7%             |
| Lithium disilicate       | LE1              | 0.0%             | 100.0%           | 0.0%             | 0.0%             |
|                          | LE2              | 0.0%             | 0.0%             | 62.2%            | 37.5%            |
|                          | LE3              | 0.0%             | 100.0%           | 0.0%             | 13%              |
| Post and core- crown (PC)|                  | 25.0%            | 0.0%             | 25.0%            | 50.0%            |
| Total                    |                  | 3.7%             | 38.9%            | 13.0%            | 44.4%            |

Fig. 4. Different designs and failure mode after static loading. Z; zirconia material, L; lithium disilicate material and PC; control group. A- Flat occlusal table. B- Circumferential ferrule. C- Buccal ferrule preparation. D- Post-and-core crown.
etching of enamel used in this study aimed to achieve a durable bonding and to preserve the marginal integrity, as it had been reported to have superior results based on a clinical observation period of 8 years [49]. In terms of zirconia surface pre-treatment, the use of mechanical and chemical pre-treatment combined appeared to achieve the best adhesion results, as in the case of the MDP phosphate monomer (10-methacryloyloxydecyl dihydrogen phosphate) [16, 50]. Increasing the size of the abrasive particles and/or air pressure would increase the surface roughness of zirconia, and would be also accompanied by prominent edges on the surface, that could impair the wettability of the zirconia surface by resin cement, resulting in lower bond strength [51]. The durable long term bonding to zirconia seems to be utilized with low-pressure air particle abrasion combined with MDP containing primers [52]. Moreover, MDP/silane containing primers have been used successfully for both ceramic materials used in the current study [50, 53].

A sample size of 8 specimens was used for the presented study, as the chewing simulator accepts only 8 samples test. This sample size was following previous studies on endocrowns with the same protocol [11, 54, 55], showing that this sample size allowed to detect the statistically significant differences. However, by increasing sample size, the statistical outcomes would be powerful.

Regarding the two materials used in the current study, zirconia (4YSZ) revealed significantly higher mean fracture strength in comparison to lithium disilicate, but only for the flat occlusal preparation design and the buccal ferrule design (ZE1 vs. LE1 and ZE3 vs. LE3). The groups with circumferential ferrules showed no significant difference in the mean fracture strength values (LE2, ZE2, and PC). The superiority of zirconia fracture strength seems to reflect its higher flexural strength and fracture toughness [16].

The mean fracture strength of the group ZE1 (1391 N) was comparable to the PC control group (1440 N), while the lithium disilicate with the same preparation (PC) showed a relatively low mean fracture strength (870 N). However, this relatively low value still acceptable for clinical application, based on previous studies that measured the maximum occlusal biting forces [56, 57], and in comparison to the results exhibited in the other laboratory studies [15, 58]. Some laboratory studies comparing endocrowns to post-and-core crowns are contradicting the results of the current study. For mandibular molars [13, 58], maxillary [59] and mandibular premolars [14, 19], endocrowns showed higher fracture strength than the post-and-core crowns, the relatively lower fracture strength of post-and-core crown specimens reported in those laboratory studies might be due to the absence of the ferrule effect on post-and-core crown specimens and the extension of the endocrown preparation up to 5 mm within the pulp [13, 14, 19, 58].

For the second design with circumferential ferrule preparation and the PC control group, the ferrule effect increased the fracture strength values for the post-and-core crowns, zirconia and lithium disilicate endocrowns (PC, ZE2, and LE2), which agreed with the results of previous studies that showed the positive influence of ferrule effect on mandibular molars [11, 12]. It is important to notice that in laboratory studies, which compared the flat occlusal table endocrowns to the post-and-core crowns without ferrules, a higher fracture strength of endocrowns than post-and-core crown groups was revealed [13, 14, 58, 59]. Obviously, with ferrule absence, endocrowns showed a better fracture strength than post-and-core crowns, which underscores the importance of the ferrule effect for post-and-core crowns [44].

However, all specimens survived the thermomechanical fatigue test under 10 kg load for 1,200,000 chewing cycles, the endocrown designs with the buccal ferrule preparation revealed a relatively lower fracture strength in comparison to the other groups. This may be related to the fact that in endocrowns with the ferrule only on the buccal surface the buccal wall of dentin is trapped between the pulpal inlay and the buccal margin of the endocrown, which might weaken the buccal surface of the specimens, leading to lower mean fracture strength values, especially with the absence of the reciprocal support of the lingual axial wall (Fig. 2A, and 4 C). The mean fracture values of groups ZE3 and LE3 groups were 857 N and 661 N, respectively. Nevertheless, the lowest mean fracture of group LE3 still higher than the highest estimated occlusal chewing forces [56]. The results of the present study lead to a free choice between the different designs and materials for clinical application, but the groups PC, ZE1, ZE2, and LE2 seem to be more reliable.

The mode of failure was interpreted according to the fracture line location and was categorized into favourable and non-favourable failures. A fracture that located apical to the CEJ, in which a vertical or oblique fracture involved the root, the clinical prognosis considered to be poor and therefore it has been named unfavourable. Conversely, a fracture in the tooth coronal to the CEJ considered to be repairable and have been named favourable [20]. In general, cracks initiate and propagate through the weakest part of the specimens, so that the percentage of fracture locations seems to have a relation to the fracture strength values and the design of preparation, wherewith higher values and the presence of enough coronal support, the fracture tend to be within the root. The teeth that resist even more load, had a better chance to break through the restoration. The ferrule design for endocrown and post-and-core crown groups have better support against an oblique quasistatic load, instead of generating stresses in all directions, the ceramic band that encircles the cervical coronal part of the specimens distributes the force more evenly and converts the weak ceramic-tooth interface to a strong once [60].

All specimens revealed non-repairable failure except for only two PC specimens, which had a favourable fracture pattern. The endocrown specimens all ended up with a catastrophic failure. The mode of failure coincides with a previous study, which stated that the use of the posts reduces the incidence of catastrophic failures [61]. There are some laboratory studies with a more favourable failure percentage for maxillary premolar endocrowns, but the bone level (2 mm cervical to CEJ) was considered the reference point for the repairable and non-repairable failure [15, 59], unlike the current study, in which the repairable failures were limited only to the coronal structures. Other studies on mandibular premolar [14] and mandibular molar teeth [12, 13] also revealed a very high catastrophic rate of failure.

Applying the occlusal force perpendicular to the occlusal plane of premolar endocrown results in a wedge-like fissure extended mesiodistally [10]. Directing the quasistatic load in an oblique direction, simulates the occlusal forces during lateral excursions, would result in fracture patterns that coincide with the anatomical form of premolar teeth and imitate the preparation design patterns [23]. The fracture load direction in the current study was at 150° to the long axis of the teeth, which according to a previous study had no difference from the force applied at 110° or 130° [62].

For medium and severely destructed endodontically treated teeth, endocrowns are one of the modern treatment modalities used [9, 63]. To get an even cavity preparation and to obliterate the undercuts, a composite base material is recommended [4]. Formerly the presence of ferrule support together with the post-and-core crown was the gold standard treatment for severely destructed endodontically treated teeth. With the development of adhesive techniques and materials, the presence of only three walls of ferrule support is considered to be enough to restore the coronal part [3]. Further, endocrowns as monobloc restorations assumed to have the advantage of reducing unnecessary strains in between the restoration interfaces [6]. As some clinical studies recommended endocrowns for molars [7, 8, 18], another clinical survey found that endocrowns could be reliable on premolars, even with the presence of occlusal risk factors. However, the long-term success rate of endocrowns reported being only 54.9 %, to gain a high success rate, proper adhesive techniques and suitable materials should be used [63]. In the current study, the use of resin cement after using a special ceramic primer containing both MDP primer and silane aimed to achieve a durable bond on both zirconia and lithium disilicate. In addition to using the tooth primer with for durable bonding to both enamel and dentin [64], may have led to the survival of all specimens after 5 years simulated artificial chewing without reporting any debonding or fractures. This confirmed that strong adhesive bonding with luting resin can noticeably strengthen weaker ceramic restorations and may balance the inherent strength variations among different materials [65].

Increasing the surface area of adhesion for endocrown in case of circumferential ferrule results in high fracture strength. The ferrule designs for lithium disilicate endocrowns revealed some difficulties during milling of the restorations, due to the limited milling area between pulpal inlay and the proximal axial ferrule walls. Those difficulties were not encountered.
in the case of zirconia specimens, because they had been milled about 23% larger than lithium disilicate specimens, to compensate for the linear sintering shrinkage of zirconia ceramic.

Nevertheless, the present study had some limitations as: studying the same designs and materials on single canal upper or lower premolars with more consistent root anatomy or using different post-and-core crown materials might show different outcomes. Specimens were limited to eight per group, the simulation of the oral cavity was carried out artificially, using distilled water, rather than using artificial saliva or drinks. The factors that influence the fracture strength of endocrowns are numerous; they might be related to the amount of tooth substance loss, preparation depth, adhesion conditions, and different restorative materials. Our study was limited to three different designs and two ceramic materials. Further investigations will be required regarding other factors.

5. Conclusion

The circumferential ferrule design encountered a better distribution of strain throughout the specimens, resulting in high fracture strength for endocrowns. The tested materials showed no significant effect in the case of circumferential ferrule design. For flat occlusal table design, 4YSZ zirconia specimens showed significantly higher mean fracture strength than lithium disilicate specimens.

Clinical significance

Endocrowns for premolars could be a very promising treatment alternative to post-and-core crowns, however further clinical and laboratory investigations with various ceramic materials and post-and-core techniques are recommended.

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Conflict of interest

The authors declare that there is no conflict of interest.

References


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