Fracture strengths of endocrown restorations fabricated with different preparation depths and CAD/CAM materials

Burcu KANAT-ERTÜRK1, Serkan SARIDAĞ1, Ege KÖSELER1, Dilek HELVACIOĞLU-YIĞIT2, Egemen AVCU3 and Yasemin YILDIRAN-AVCU4

1 Department of Prosthodontics, Kocaeli University, Faculty of Dentistry, Başiskele, Kocaeli, Turkey
2 Department of Endodontics, Kocaeli University, Faculty of Dentistry, Başiskele, Kocaeli, Turkey
3 Department of Machine and Metal Technologies, Kocaeli University, Ford Otosan İhsaniye Automotive Vocational School, Gölcük, Kocaeli, Turkey
4 Department of Mechanical Engineering, Kocaeli University, Faculty of Engineering, İzmit, Kocaeli, Turkey

Corresponding author, Burcu KANAT-ERTÜRK, E-mail: burcu.erturk@kocaeli.edu.tr

The objectives of this study were to compare the fracture strength of endocrown restorations fabricated with different preparation depth and various CAD/CAM ceramics, and to assess the fracture types. Endodontically treated 100 extracted human permanent maxillary centrals were divided into two preparation depth groups as short (S: 3-mm-deep) and long (L: 6-mm-deep), then five ceramic subgroups, namely: feldspathic-ceramic (Vita Mark II-VM2), lithium-disilicate glass-ceramic (IPS e.max CAD-E.max), resin-ceramic (LAVA Ultimate-LU), polymer infiltrated ceramic (Vita Enamic-VE) and monoblock zirconia (inCoris TZI-TZI) (n=10/subgroup). The endocrowns were fabricated by CAD/CAM and were cemented with resin cement (RelyX U200). The teeth were thermally cycled (5,000 cycles) and fracture tests were performed at 45° angle to the teeth. The data were statistically analyzed (Kruskal-Wallis, Mann Whitney U), failure modes were evaluated with stereomicroscopy. Zirconia group provided the statistically highest fracture strength, but also exhibited non-repairable failures. Preparation depth has an effect on the fracture strength only for feldspathic ceramic.

Keywords: Endocrown restoration, CAD/CAM, Preparation depth, Full ceramic, Fracture strength

INTRODUCTION

Rehabilitation of the endodontically treated teeth with severe crown damages presents a clinical challenge, because the poor structural integrity resulting from caries and/or cavity preparation leads to higher risk of teeth fracture1,2. While making a decision on the treatment of the dehydrated teeth with extensive loss of coronal structure, it should be aimed to protect and strengthen the remaining teeth3. Therefore, the material and prosthetic treatment choices play an important role in the longevity of both the restoration and the devital teeth4.

The conventional treatment approach for endodontically treated teeth with coronal substance loss is known as a crown restoration which is built on the root canal by post5. Previous studies have emphasized that sufficient ferrule effect increases the fracture resistance of restored teeth6,7. In addition to the remaining tooth structure, the post types also play a significant role on the clinical behavior of the endodontically treated teeth. Whereas metal posts may cause non-repairable fracture of the root because of higher stress distribution8, fiber posts which have similar elasticity moduli with dentine may overcome this problem9. Moreover, several studies in the literature have reported that the application of the posts causes weakening of the roots, in addition to the perforation risk during the preparation of the post space10,11. As of yet, there is no established consensus on whether the post length affects the fracture resistance of teeth. Despite some works in the literature which state that longer posts lead to higher fracture resistance12, some studies show that there is no statistical difference between the long and short posts in terms of fracture resistance of teeth13,14.

With the improvement of adhesive dentistry, endocrown restorations have been developed as an alternative to post-core systems in the restoration of teeth with severe crown damages. Endocrowns, which were introduced by Pissis in 1985, are monoblock restorations combining the core structure with crown restoration15. Endocrown restorations are fulfilled without the post application by utilizing the macro-retentive support of the pulp chamber walls and the micromechanical retention due to adhesive cementation16. This way, the pulp canals and the healthy coronal tooth tissues, which are removed during post and crown preparations respectively, can be protected. Moreover, the teeth without adequate ferrule effect and interocclusal space for both core and crown materials can be rehabilitated with the endocrown restorations, which also saves time for both the dentist and the patient by eliminating the laboratory stages required for the conventional crown restoration17. The other advantage of the endocrowns is that the number of stages, resulting from using different materials such as cement, post, core and crown, are reduced. It has also been reported in the literature that the stresses which are accumulated at the interfaces of the different materials with different...
elasticity moduli may cause increased root fracture risk, which is also reduced in endocrown restorations\(^{9,10}\).

Sedrez-Porto et al.\(^{20}\) compared the endocrown and conventional restorations such as post, inlay/onlay, direct composite in the systematic review and meta-analysis including 3 clinical and 5 in vitro studies. The success rate of the endocrowns was reported between 94 and 100% according to 3 clinical trials used in the systematic review. Moreover, according to the in vitro studies, it was stated that there were not statistically significant differences between endocrown and conventional treatments in posterior area, whereas endocrown restorations showed higher fracture strength values than conventional restoration in anterior and posterior areas\(^{20}\). Bindl et al.\(^{21}\) also reported that endocrown restoration could be clinically acceptable for molar teeth with 87.1% survival rate, whereas 97.0% survival was observed for classic crowns in 55±15 months follow-up. But for premolars, the endocrowns were stated inadequate due to 68.8% survival rate versus 94.6% survival observed for classic crowns\(^{21}\).

Computer aided design/computer aided manufacturing (CAD/CAM) system which is widely used in dental applications nowadays, allows the restoration to be produced with more precise marginal adaptation in reduced time\(^{22,23}\). As most laboratory and clinical procedures are eliminated with respect to conventional fabrication techniques, the restorations are manufactured economically and without errors which may be composed during the restoration process\(^{23,24}\). Moreover, interim prosthesis is not necessary due to the fabrication of the restorations in chairside by using CAD/CAM. Therefore, endocrown restorations which have a smaller number of processes can be manufactured faster and easier than conventional post-core systems, with the advantages of digital dentistry\(^{25,26}\).

In parallel with the developments and improvements in CAD/CAM, new and varied ceramic materials with different mechanical and aesthetic properties are continually being developed\(^{27}\). Leucite reinforced ceramics were developed to provide a more aesthetic outcome with respect to feldspatic ceramics, lithium disilicate reinforced ceramics were manufactured to obtain enhanced flexibility and fracture resistance of 400 MPa, and monolithic zirconia ceramics were introduced to eliminate the chipping problem of superstructures. In addition to these ceramic materials, composite based materials such as resin-ceramic and polymer infiltrated ceramic have been developed to obtain elasticity moduli similar to dentine, and therefore enable stress absorbance\(^{28,29}\). Therefore, nowadays, dentists have a great opportunity to select appropriate and favorable materials for restorations, among this large array of ceramics. However, dentists have to consider the biomechanical behavior of these materials in order to make a well-informed decision. This makes the comparisons of the materials in terms of biomechanical behavior and performance an ongoing and important research topic.

Although some literature exists which compare the fracture resistance of endocrown restorations fabricated by various CAD/CAM blocks, there is no data about the effect of preparation depth on fracture strength for endocrown restoration fabricated by CAD/CAM materials on the first incisor teeth. The aim of this in-vitro study was to investigate the effects of a multitude of recent and benchmark CAD/CAM materials, and preparation depths on the fracture strength and fracture modes of central endocrown restorations. The null hypotheses of this study were that 1) the various CAD/CAM materials would not affect the fracture strength of endocrown restorations, 2) the preparation depth has no influence on the fracture strength of central endocrown restorations, 3) the failure type would not be affected from the CAD/CAM materials and preparation depths.

**MATERIALS AND METHODS**

One hundred already extracted maxillary central human first incisors, which have similar dimensions as well as being without caries, root fracture or endodontic treatment, were used in this study. The teeth were stored in distilled water and were sectioned horizontally 1-mm above the enamel-cement junction under water cooling using a diamond bur. This study was approved by the ethical review board of the University (KOU KAEK 2015/97).

**Endodontic treatment and root preparation**

A size of 10 K-file (Mani, Tochigi, Japan) was placed passively in each root canal until it reached the apical foramen. The working length was 0.5-mm shorter than the measured length. Root canals of specimens were prepared using ProTaper Universal (PTU) rotary instruments up to size 50 (F5) operated with a torque-limited motor (VDW silver, VDW, Munich, Germany). The root canals were irrigated with 2 mL 1% NaOCl solution after each instrument change. Following instrumentation each canal was irrigated with 5 mL of 17% EDTA, 5 mL of 1% NaOCl and a final rinse with 5 mL distilled water. The root canals were dried with paper points (Diadent, Seoul, Korea). Root canals were then obturated using cold lateral compaction of gutta-percha with AH Plus sealer (DeTrey Dentsply, Kontanz, Germany). Excess root filling in the coronal portion was removed 1-mm below the cementoenamel junction and vertically condensed with a heated plugger. The canal openings were sealed with temporary filling material (Cavit, 3M ESPE, Seefeld, Germany). Teeth were stored at 37°C with 100% humidity for one week to allow the sealer to set.

Following the endodontic treatment, the teeth were randomly divided into two groups depending on the preparation depth of the endocrowns [short: 3-mm (S), long: 6-mm (L)] (n=50/preparation group). The large drill with 1.5-mm-diameter (Reforpost size 5, Angelus, Londrina, Brazil) was used to remove the gutta-percha by using a low-speed micromotor. The preparation depth was standardized with silicone stopper positioned on the drill to obtain 3- and 6-mm from the base of the canal.
for S and L groups, respectively. Then the cavity base and inner surfaces were adjusted with diamond bur for onley (Komet Jewellery, Brasseler, Lemgo, Germany) to obtain homogenous surfaces and minimize the internal stresses. The preparation depths in the teeth canals were controlled using a periodontal probe. All the root preparations were carried out by the same operator.

**Preparation of endocrowns**

All specimens in L and S groups were randomly divided into 5 subgroups and manufactured with different CAD/CAM blocks, namely feldspathic ceramic (Vita Mark II, Vita Zahnfabrik, Bad Säckingen, Germany) (VM2) lithium disilicate glass-ceramic (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein) (E.max), resin-ceramic (LAVA Ultimate, 3M ESPE) (LU), polymer infiltrated ceramic (Vita Enamic, Vita Zahnfabrik) (VE) and monoblock zirconia (inCoris TZI, Sirona Dental Systems, Bensheim, Germany) (TZI) \( n = 10 \) /subgroup. The brand names, types, manufacturers, chemical compositions and batch numbers of the materials used in this study are listed in Table 1.

Following the endodontic treatment and root preparation, each tooth was positioned on the maxillary right first incisor tooth location of the artificial study jaw model (Kavo Dental, Biberach, Germany) so that the preparation margin of the roots are at the same level. The first incisor tooth location was selected to benefit from the symmetric central tooth image by using the biogeneric reference option in CAD/CAM, in order to standardize the form of all endocrowns. The restoration form in the CAD/CAM software (CEREC AC, Sirona InLab V4.2.5; Sirona Dental Systems) was selected as crown for the maxillary right first incisor and biogeneric reference option was selected. Digital impressions were obtained by using intraoral scanner (Bluecam, Sirona Dental Systems) after each tooth was covered with a labside contrast spray (Cerec Optispray, Sirona Dental

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<tbody>
<tr>
<td>inCoris TZI</td>
<td>TZI</td>
<td>Sirona Dental Systems, Bensheim, Germany</td>
<td>Monoblock zirconia, ( \text{ZrO}_2+\text{HfO}_2+\text{Y}_2\text{O}_3 \geq 99.0 ), ( \text{Y}_2\text{O}_3 &gt;4.5\leq6.0), ( \text{HfO}_2 \leq 5), ( \text{Al}_2\text{O}_3 \leq 0.5), Other oxides ( \leq 0.5 )</td>
<td>210</td>
<td>&gt;900</td>
<td>2014161366</td>
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<tr>
<td>IPS e.max CAD</td>
<td>E.max</td>
<td>Ivoclar Vivadent, Schaan, Liechtenstein</td>
<td>Lithium-disilicate glass-ceramic, ( \text{SiO}_2 (57\sim80) ), ( \text{Li}_2\text{O} (11\sim19) ), ( \text{K}_2\text{O} (0\sim13) ), ( \text{P}_2\text{O}_5(0\sim11) ), ( \text{ZrO}_2(0\sim8) ), ( \text{ZnO} (0\sim8) ), Other and coloring oxides ( 0\sim12 )</td>
<td>95</td>
<td>360</td>
<td>U51702</td>
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<tr>
<td>Vita Enamic VE</td>
<td>VE</td>
<td>VITA Zahnfabrik, Bad Säckingen, Germany</td>
<td>Polymer infiltrated ceramic, ( \text{SiO}_2 (58\sim63) ), ( \text{Al}_2\text{O}_3 (20\sim23) ), ( \text{Na}_2\text{O} (9\sim11) ), ( \text{K}_2\text{O} (4\sim6) ), ( \text{B}_2\text{O}_3 (0.5\sim2) ), ( \text{ZrO}_2 (&lt;1) ), ( \text{K}_2\text{O} (&lt;1) )</td>
<td>30</td>
<td>150\sim160</td>
<td>41470</td>
</tr>
<tr>
<td>Vita Mark II VM2</td>
<td>VM2</td>
<td>VITA Zahnfabrik</td>
<td>Feldspathic-ceramic, ( \text{SiO}_2 (56\sim64) ), ( \text{Al}_2\text{O}_3 (20\sim23) ), ( \text{Na}_2\text{O} (6\sim9) ), ( \text{K}_2\text{O} (6\sim8) ), ( \text{CaO} (0.3\sim0.6) ), ( \text{TiO}_2 (0\sim0.1) )</td>
<td>63</td>
<td>154</td>
<td>44330</td>
</tr>
<tr>
<td>Lava Ultimate LU</td>
<td>LU</td>
<td>3M ESPE, Seefeld, Germany</td>
<td>Resin-ceramic, Polymerized dental restorative, consisting of silica nanomers (20 nm), zirconia nanomers (4–11 nm), nanocluster particles derived from the nanomers (0.6–10 μm), silane coupling agent, resin matrix</td>
<td>12.77</td>
<td>204</td>
<td>N603340</td>
</tr>
<tr>
<td>Rely X U200</td>
<td>—</td>
<td>3M ESPE</td>
<td>Base paste: Methacrylate monomers containing phosphoric acid groups, Methacrylate monomers, Silanated fillers, Initiator components, Stabilizers, Rheological additives</td>
<td>6.6</td>
<td>99</td>
<td>545768</td>
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Circumferential margin and insertion path of the restoration were determined according to the part of the endocrown in the root canal (Fig. 1a). The thickness of the die spacer was selected as 10 µm to decrease the rotation of restoration during fracture test. On all of the 100 digital impressions, which included 2 different preparation depths as S (3-mm) and L (6-mm) (n=50/preparation group), the endocrowns were designed (Figs. 1b–d) and milled (InLab MC XL, Sirona Dental Systems) out of the CAD/CAM blocks matched with each subgroup: feldspathic ceramic (Vita Mark II), lithium disilicate glass-ceramic (IPS e.max CAD), resin-ceramic (LAVA Ultimate), polymer infiltrated ceramic (Vita Enamic) and monoblock zirconia (inCoris TZI). During the milling process, presintered zirconia blocks were milled with 20 to 25% enlarged volume to compensate for shrinkage after the sintering process, whereas the remaining ceramic groups were obtained with the final dimensions.

The milled zirconia endocrowns were sintered (InFire HTC speed, Sirona Dental Systems), and the milled lithium disilicate endocrowns were subjected to crystallization firing (Programat P300, Ivoclar Vivadent) to convert crystalline intermediate (metasilicate-in blue color) stage of the ceramic into the disilicate phase and to improve the flexural strength. Then, the adaptations of the manufactured restorations with teeth were checked. Endocrown restorations in VM2, E.max, VE and TZI were glazed [(Vita Akzent, Vita Zahnfabrik for VM2), (IPS e.max Ceram Glaze, Ivoclar Vivadent for E.max), (Vita Enamic Glaze, Vita Zahnfabrik for VE), (CEREC SpeedGlaze spray, Sirona Dental Systems for TZI)], whereas the endocrowns in LU group were polished (Meisinger Tool Set for Lava, Hager & Meisinger, Neuss, Germany), in accordance with the manufacturers' instructions.

Prior to the cementation process, all the endocrowns were steam cleaned. The inner surfaces of the restorations in VM2 and VE groups were etched with 9.5% hydrofluoric acid gel (Ultradent Porcelain Etch, Ultradent, South Jordan, UT, USA) for 30 s, and the restorations in E.max group were etched with 9.5% hydrofluoric acid gel (Ultradent Porcelain Etch) for 10 s. Then, the restorations in these three groups were rinsed for 10 s with running water, and dried for 5 s. Airborne-particle abrasion was performed with 50-µm aluminum oxide particles at a pressure of 2.5 bar for 4 s to the inner surfaces of TZI and LU groups, and the inner surfaces were cleaned with alcohol and dried with oil-free air. VM2, E.max and VE were etched with hydrofluoric acid in order to obtain microporosities for micromechanical retention26,30), according to the manufacturers’ instructions29). But, TZI, which does not include silicate phase unlike glass-ceramics, should be subjected to airborne-particle abrasion for the adhesive cementation31). Moreover, in the adhesive cementation of LU, it has been reported that airborne-particle abrasion leads to higher adhesive strength and micromechanical retention32), as also recommended in the manufacturer’s instructions29). In short, the surface conditioning for all groups was performed in accordance with the manufacturers’ instructions and relevant literature, to obtain the best performance for each of the materials. The silane (Monobond Plus, Ivoclar Vivadent) was applied to all groups by using a microbrush and dried for 10 s, after a waiting duration of 60 s. The enamel surfaces of
prepared teeth were etched with 37% phosphoric acid gel for 20 s, rinsed and dried with oil-free air for 5 s. The dual-cure self-adhesive resin cement (RelyX U200, 3M ESPE) was applied to the prepared root canals, by lentulo spiral, and the inner part of endocrowns, and then the crowns were seated in the appropriate position with finger pressure. All conditioning and bonding procedures were carried out by the same operator. After the cleaning of the remnants by using a microbrush, the combination was photopolymerized for 40 s from each surface, and then the margins were polished. Following 48 h storage in distilled water, the specimens were subjected to thermal cycling at temperatures of 5 and 55°C for a total of 5,000 cycles. Dwell time at each temperature was 30 s, and transfer time was 2 s.

Prior to the mechanical fracture test, roots of teeth were covered with a 0.2-mm layer of polyether impression material (Impregum Garant L DuoSoft, 3M ESPE) to simulate the periodontal ligament (PDL) and embedded in an auto-polymerizing acrylic resin (Meliodent, Heraeus Kulzer, Hanau, Germany) up to 2-mm below the cementoenamel junction.

Fracture test and failure analysis
Fracture tests at 45 degrees angle to the long axis of the teeth were performed in a universal testing machine (Instron 4411, Instron, High Wycombe, UK) at a cross-head speed of 1 mm/min until fractures occurred (Fig. 2). In this study, 45 degrees angle was selected to mimic intraoral conditions so that the force was conducted in both the axial and the lateral directions. Then, all fractured surfaces were analyzed using a stereo-microscope (Olympus SZ4045 TRPT, Osaka, Japan) at ×20 magnification to identify the failure modes. After the assessment of all specimens, failure types were defined either as a) debonding of endocrown (Type I), b) fracture of endocrown (Type II), c) Fracture of the endocrown/tooth complex above the enamel-cement junction (Type III), and d) Fracture of the endocrown/tooth complex below the enamel-cement junction (Type IV). Types I, II and III were called as “repairable” failures, whereas fracture in Type IV was termed as “non-repairable” failures. The periapical X-rays were obtained to select the restorations for Type III and Type IV.

Statistical analysis
The fracture strength values (Mean±SD; median, min, max) between ceramic groups were statistically analyzed in NCSS 2007 (Number Cruncher Statistical System, Kaysville, UT, USA) by Kruskal Wallis and Benforroni corrected Mann Whitney U. Values less than 0.005 were considered to be statistically significant. In addition, Mann Whitney U test was utilized to statistically analyze the effect of preparation depth on the fracture strength values, for each ceramic group (p<0.05).

RESULTS
The fracture strength values (Mean±SD; median, min, max) are presented in Table 2. For L preparation depth group, TZI group (610.54±214.04) showed statistically highest values (p=0.001). The differences between E.max (225.08±125.36) and VE (182.38±106.52) groups, VE (182.38±106.52) and LU (99.80±33.62) groups, and VM2 (71.38±23.56) and LU (99.80±33.62) groups were statistically insignificant (p>0.005). The lowest values were obtained in VM2 group (71.38±23.56) overall. VM2-L group showed statistically higher fracture strength values with respect to VM2-S group (p=0.014), whereas for the other ceramic groups L and S preparation depths were not found statistically significant (p>0.05) (Table 3).

Failure type ratios for each ceramic and preparation depth group are presented in Table 4. According to the failure type distributions, no debonding failures (0% Type I) were observed for any group. Specimens in VE, LU and VM2 ceramic groups, with both short and long preparation depths, showed 100% Type II failure, which was defined as a fracture of the endocrown. E.max-L and E.max-S ceramic groups showed mostly Type II (80 and 90%, respectively) and occasionally Type III failures (20 and 10%, respectively). The catastrophic failures, i.e. Type IV, were observed only in TZI groups, 40 and 10% for TZI-L and TZI-S, respectively. Two examples for Type II failures can be observed Figs. 3a–b, in which
Table 2  Fracture strength values (N) of endocrowns prepared with different CAD/CAM materials and preparation depths

<table>
<thead>
<tr>
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<th>Long preparation (L) group</th>
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<th>Short preparation (S) group</th>
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<tr>
<td></td>
<td>N</td>
<td>Mean (SD) (N)</td>
<td>Median (min–max)</td>
<td>N</td>
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<tr>
<td>Monoblock Zirconia (TZI)</td>
<td>10</td>
<td>610.54 (214.04)&lt;A,A</td>
<td>590 (358.4–920)</td>
<td>10</td>
</tr>
<tr>
<td>IPS E.max CAD (E.max)</td>
<td>10</td>
<td>225.08 (125.36)&lt;B,B</td>
<td>163.40 (106.3–445)</td>
<td>10</td>
</tr>
<tr>
<td>Vita Enamic (VE)</td>
<td>10</td>
<td>182.38 (106.52)&lt;C,C</td>
<td>150.95 (69.3–361)</td>
<td>10</td>
</tr>
<tr>
<td>Lava Ultimate (LU)</td>
<td>10</td>
<td>99.80 (33.62)&lt;D,D</td>
<td>102.80 (44.7–146.5)</td>
<td>10</td>
</tr>
<tr>
<td>Vita Mark II (VM2)</td>
<td>10</td>
<td>71.38 (23.56)&lt;E,E</td>
<td>72.86 (42.7–108.3)</td>
<td>10</td>
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Same superscript small letters represent no significant difference in the column, same superscript capital letters indicate no significant difference in the row.

Table 3  Mann Whitney U results for long and short preparation depth within each ceramic group

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<th>Long - short preparation depth</th>
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<td>p</td>
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<tr>
<td>Monoblock Zirconia (TZI)</td>
<td>0.364</td>
</tr>
<tr>
<td>IPS E.max CAD (E.max)</td>
<td>0.705</td>
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<tr>
<td>Vita Enamic (VE)</td>
<td>0.650</td>
</tr>
<tr>
<td>Lava Ultimate (LU)</td>
<td>0.130</td>
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<tr>
<td>Vita Mark II (VM2)</td>
<td>0.014</td>
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Table 4  Ratios of failure types distributions (%) of the groups

<table>
<thead>
<tr>
<th></th>
<th>Monoblock Zirconia</th>
<th>IPS E.max CAD</th>
<th>Vita Enamic</th>
<th>Lava Ultimate</th>
<th>Vita Mark II</th>
</tr>
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<tbody>
<tr>
<td>Type I</td>
<td>TZI-L</td>
<td>TZI-S</td>
<td>E.max-L</td>
<td>E.max-S</td>
<td>VE-L</td>
</tr>
<tr>
<td>Type II</td>
<td>40</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>Type III</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>Type IV</td>
<td>40</td>
<td>10</td>
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Type I: Debonding of endocrown, Type II: Fracture of endocrown, Type III: Fracture of the endocrown/tooth complex above the enamel-cement junction, Type IV: Fracture of the endocrown/tooth complex below the enamel-cement junction.

the inner parts of the endocrowns were fractured and remained in the root canal. Two examples for Type IV failures are presented in Figs. 3c and 3d. In Fig. 3c, the tooth part which was fractured under the enamel-tooth junction was bonded to the endocrown in TZI-L group. In the Type IV failure in Fig. 3d, the root crack extended to under the enamel-cement junction in TZI-S group. The representative periapical X-rays belonging to Type II, Type III and Type IV failures can be seen in Figs 4. In Type II failure, only fracture of endocrowns was observed as indicated with an arrow in Fig. 4a. In Type III failure, the crack of the root ended above the enamel-tooth junction as shown in Fig. 4b, whereas the cracks for 4 specimens in Z-L and for 1 specimen in Z-S
DISCUSSION

In the present study, the effects of various CAD/CAM materials and different preparation depths were investigated for the fracture strengths and fracture modes of endocrown restorations on first incisors. The null hypotheses of this study were that 1) the various CAD/CAM materials would not affect the fracture strength of endocrown restorations, 2) the preparation depth has no influence on the fracture strength of central endocrown restorations, 3) failure type would not be affected from the CAD/CAM materials and preparation depths. The first null hypothesis was rejected, because CAD/CAM materials did affect the fracture strength, such that the highest and the lowest fracture strength values were obtained in zirconia and feldspathic groups, respectively. In addition, the fracture strength values for zirconia were statistically significant with respect to all other CAD/CAM blocks. The second null hypothesis was partially rejected, as for the VM2 group, different preparation depths resulted in a significant difference of fracture strength. The third was rejected, as catastrophic failures were only observed in zirconia groups, whereas the other CAD/CAM blocks resulted in only repairable fractures.

Endocrown restorations have been increasingly used for the treatment of teeth with severe crown damages, in addition to conventional crown restorations supported by post-core systems. In the literature, the oblique fracture strength of endocrown and conventional crowns on glass fiber post-composite core were compared, and higher fracture values were found for endocrowns (674.75 N) with respect to conventional post-core systems (469.90 N)(36). Also, Chang et al.(37) stated that leucite-reinforced glass ceramic endocrown restorations showed statistically higher fracture resistance values (1,446.68 N) than all-ceramic crowns supported...
by glass fiber post and composite core (1,163.30 N) for premolars. These results were attributed to the increased thicknesses of the ceramic materials and the reduced number of interfacial surfaces for endocrowns with respect to post-core crowns. In an in-vivo study by Bindl and Mörmann, it was presented that only one in 19 endocrowns failed due to recurrent caries, after a 28 months clinical follow-up. Also, finite element analysis studies revealed that endocrowns were more resistant to failures than crowns with post-core systems, because of their lower stress values. In light of the literature, in this study, it was decided to focus only on endocrowns modified with different materials and designs, and post core systems were not included.

It has been reported that several factors play an important role on the performance and longevity of ceramic restorations, such as the strength and thickness of the ceramic, the compatibility of the elastic moduli of the ceramics and tooth, and the adaptation of the restorations to the interfacing bonding surface. The study which compared the mechanical properties of feldspathic ceramic (Vita Mark II), lithium disilicate reinforced glass ceramic (IPS e.max CAD) and polymer infiltrated ceramic (Vita Enamic) by three-point bending test, reported that lower flexural strength values were found for feldspathic ceramic (106.67±18.50 MPa) with respect to lithium disilicate reinforced glass ceramic (341.88±40.25 MPa) and polymer infiltrated ceramic (145.95±12.65 MPa). Similarly, Albero et al. reported that feldspathic ceramic (Vita Mark II) provided lower fracture strength values with respect to lithium disilicate reinforced glass ceramic (IPS e.max CAD), polymer infiltrated ceramic (Vita Enamic) and resin-ceramic (LAVA Ultimate). There are some studies which examine the performance of ceramic materials for endocrown restorations in terms of fracture strength. Various CAD/CAM blocks with different elasticity moduli were evaluated for molar endocrown restorations, and it was reported that the highest fracture strengths were observed in resin-ceramic group (Lava Ultimate) (1,583.28 N), whereas there were no statistically significant differences between the feldspathic (Cerec blocks) (1,340.92 N) and the lithium disilicate reinforced glass ceramic (IPS e.max CAD) (1,368.77 N). From the point of failure modes, while only repairable fractures were observed in resin-ceramic group, catastrophic failures, as much as 70%, were seen in the lithium disilicate group. On the other hand, Aktas et al. found that different CAD/CAM materials such as alumina silicate ceramic (Vita Mark II), zirconia-reinforced glass ceramic (Vita Suprinity) and polymer-infiltrated ceramic (Vita Enamic) with different elasticity moduli have no statistically significant effect on the fracture strength of molar endocrowns. But, all the specimens in zirconium-reinforced lithium disilicate group showed catastrophic failures, also known as non-repairable failures, whereas mostly repairable fractures were observed in the other groups. Gresnigt et al. evaluated the fracture strength of molar endocrowns made of lithium disilicate (IPS e.max CAD) and multiphase resin composite material (Lava Ultimate) under lateral and axial static forces. No statistical difference was obtained between the materials under axial forces (2,675 and 2,428 N), whereas under lateral forces the resin composite material group showed significantly lower values (838 N) with respect to glass ceramic group (1,118 N). It was concluded that endocrown restorations are more durable under axial forces. Barreto et al. reported that the force applied at the angle of 45 degrees to the long axis of the tooth increases fracture risks due to the accumulation of the stresses at the cervical area of the tooth instead of spreading over the long axis.

In our study, the highest fracture strength of endocrowns were observed in TZI group (533.61 N for S, 610.54 N for L) which has the highest elasticity moduli and flexural strength, and the lowest values were found in VM2 (47.29 N for S, 71.38 N for L) groups, in accordance with the literatures by Leung et al. and Albero et al. The reason for lower fracture strength values obtained in our study for all groups could be attributed to the differences in crown shape (incisor instead of molar) and the force axis (45 degrees angle instead of 90 degrees angle) used in this study. The fracture types observed in the studies mentioned above were compatible with our study, since catastrophic failures, also called as non-repairable failures, extending to below the cement-enamel junction, were observed only on TZI groups, whereas only fracture of endocrowns, i.e. Type II, was observed in VE, LU and VM2 groups. The relevance of the elasticity modulus of both materials and dentin play an important role on the failure behavior of the ceramics during the loading test. The stresses observed in materials which have similar elasticity moduli with respect to dentin were spread, whereas rigid materials with higher elasticity moduli than dentin resulted in stress accumulation and catastrophic failures. Catastrophic failures occurred only for the TZI material, which has higher elasticity moduli (210 GPa) than dentin (18.6 GPa) (Figs. 3c, 3d), whereas VM2 (63 GPa), VE (30 GPa) and LU (12.77 GPa), which have similar elasticity moduli with dentin caused onlyrepairable failures, i.e. fractures of endocrowns (Figs. 3a, 3b). In E.max (95 GPa) group with higher elasticity moduli than dentin, mostly Type II failures were observed in addition to the Type III failures which called as fracture of the endocrown/tooth complex above the enamel-cement junction as 20 and 10% in E.max-L and E.max-S groups, respectively.

There are various studies in the literature on the effect of post length on fracture strength, but no data is available on the effect of preparation depths of endocrowns for central teeth. Ramirez-Sebastiá et al. reported that post application and post lengths had no effect on the fracture strength of restorations because no statistically significant differences were obtained among the endocrowns and the crowns with long glass fiber post and short glass fiber post. In other works, cavity depths were investigated in terms of marginal and internal adaptations for molars, and it was revealed...
that the discrepancy was increased with the deepening of the cavity. In our study, which investigated the effect of central teeth preparation depths on the fracture strength of endocrowns, it was aimed to provide relevant data for clinical applications. It was determined that the preparation depth affected the fracture strength only for the feldspathic ceramic group.

When the fracture strength values obtained in this study are compared with the bite forces of 150–200 N, it can be noticed that zirconia and lithium disilicate ceramic groups could be used reliably in clinical applications of endocrown restorations with long and short preparation depths, based on the results of this study. The fracture strength values of the other ceramic groups used in this study, namely feldspathic ceramic, resin-ceramic and polymer infiltrated ceramic, did not exceed the limits of bite forces. While making a decision on which ceramic material would be a better choice for clinical applications, the fracture types of the materials should also be considered, in addition to the fracture strength values. According to the failures types observed in the study, catastrophic failures occur more frequently when the zirconia material was chosen, with regards to lithium disilicate glass ceramic. The results of the study may shed light in the clinical usage of the endocrowns for central teeth, which has limited data in the literature. According to the results of this study, the selection of CAD/CAM ceramic material should be carefully considered in the application of endocrowns for central teeth, whereas preparation depths for the inner part of the endocrowns have no significant effect on the fracture strength of restorations except for feldspathic ceramic.

Whereas periodontal ligament simulation was used in some literature, there are studies which reported that periodontal ligament is challenging in terms of thickness standardization and stability. Although Marchionati et al. stated that no differences were found between the groups with and without periodontal ligament for the fracture resistance of roots treated with fiber post, Soares et al. reported that periodontal ligament affected the fracture resistance and fracture modes by behaving as a stress absorber. The authors of this study preferred to use periodontal ligament simulation prior to the fracture strength analysis of endocrowns, in order to better simulate the real tooth behavior against masticatory forces.

The limitations of the present study could be stated as not performing the forces dynamically as in chewing cycles, and not imitating the intra-oral conditions with saliva. Future studies may address these limitations, or an in vivo study may be conducted to examine the clinical performance of endocrown restorations fabricated from various CAD/CAM materials with different preparation depths.

CONCLUSIONS

From this in vitro study, the following conclusions could be drawn:

1. Zirconia and feldspathic ceramic materials show the highest and the lowest fracture resistance values, for short and long preparation depths, respectively.
2. The preparation depth has a significant effect on the fracture strength of endocrowns for feldspathic ceramic.
3. Catastrophic fractures can occur when zirconia materials with high elasticity moduli are used, whereas only repairable fractures occur when lithium disilicate, polymer infiltrated ceramic, resin-ceramic and feldspathic ceramics are used.

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