Optimizing the restoration of posterior endodontically treated teeth

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CHAPTER 4

Severely damaged endodontically treated teeth: endocrowns


N.B. The main–authors. G. T. Rocca and R. Daher both contributed equally to this publication.
Abstract

Objectives: To explore fatigue limits of ceramic endocrowns for premolars.

Methods: Forty-eight devitalized premolars were cut at the CEJ. They were restored with standardized CAD–CAM lithium disilicate reinforced ceramic restorations (IPS e.max CAD, Ivoclar-Vivadent) and divided into four Groups (n = 12): overlays (Group A, no endo-core, negative control), endocrowns with an endo-core of 2 mm (Group B), 4 mm (Group C) and crowns with post and core (Group D, positive control). All specimens were first submitted to thermo-mechanical cyclic loading (TCML) (1.7 Hz, 49 N, 600000 cycles, 1500 thermo-cycles). Margins were analysed before and after the loading. Survived specimens were then submitted to cyclic isometric stepwise loading (5 Hz, 200N to 1200N) until completion of 105000 cycles or failure. In case of fracture, fragments were analysed using SEM and failure mode was determined. Results of stepwise loading were statistically analysed by Kaplan–Meier life survival analysis and log rank test (p = 0.05).

Results: All the specimens survived the TCML test except four specimens of Group A (early restorations' debonding). No difference in percentages of closed margins was found between endocrowns (Groups B, C) and crowns (Group D). After the stepwise test, differences in survival within the groups were not statistically significant. Most of restorations experienced non-reparable fracture.
Severely damaged endodontically treated teeth: endocrowns

Introduction

Endodontically treated teeth are more fragile than vital ones\(^1\). Among different reasons for this increased weakness, it is nowadays widely accepted that the privation of tooth substance due to the previous pathology and to the endodontic treatment is the most important biomechanical alteration, influencing the long-term prognostic of the tooth\(^2,3\). When considering the restoration of devitalized teeth, dental materials should be able to replace this loss of substance in order to guarantee mechanical and functional properties, esthetics and coronal seal\(^4\).

Traditionally, this function is fulfilled by Porcelain Fused to Metal (PFM) or “full-ceramic” crowns which are usually constructed on a core fixed to the root through an endodontic post. The resistance to fracture of a devitalized tooth is related to many factors including the root canal treatment (risk of vertical root fractures), the post-core system (post material and size, core material, ferrule effect) and coronal issues (quality and quantity of remaining tissues, type of restoration, loading context)\(^5\).

Among these factors, post-retained restorations have been widely investigated but still no consensus exists on ideal materials and techniques\(^6,7\). While in the past long metal-based cast dowel and prefabricated posts were recognized as gold standards, today bonded prefabricated glass-fiber-reinforced posts (GFRP) have gained more popularity both in clinics and in research. Main reasons for this paradigm shift are a more aesthetic approach, an elastic modulus like dentinal tissues and the possibility to bond these posts inside the root via a resin-dentin interface. Due to these features, bonded GFRP are potentially able to strengthen the root by creating an endodontic “monoblock”\(^8\). Though this concept is good in theory, ideal bonding inside the root canal is still a challenge in practice. Besides the degradation of the resin-dentin interface with the time\(^9,10\) which is a generic issue met by the dentin adhesion, the peculiar anatomy of the root canal exacerbates some other concerns during adhesive application such as the tissues moisture control, the smear layer management and the adhesive volatile components removal\(^11\). Moreover, the anatomy of the canal offers an extremely unfavourable surface geometry for the
relief of the shrinkage stresses developed during resin cement polymerization. The C-factor (bonded/unbonded surfaces ratio) in a long and narrow root canal can exceed 1000 indeed\textsuperscript{12}, hindering any resin flow during hardening. Plus, all common light- and dual-polymerizable resin cements need a deep light penetration inside the canal and through the fiber post to achieve a proper degree of polymerization\textsuperscript{13,14}, which has an influence over their final bonding effectiveness\textsuperscript{15}. As a matter of fact, the need of a deep anchoring with a long GFRP has been criticized, basing on the logical assumption that all the aforementioned issues should increase with the increase of the post length\textsuperscript{8}. Also, when the invasiveness of posts over sound tissues is evaluated, the risk of root perforation and root fracture associated to long post placement should not be underestimated\textsuperscript{16,17}. In this context, monolithic CAD-CAM endocrowns, which extend inside the pulp chamber and partially inside the root canal with a short “endo-core”, could represent an alternative to classical treatments to restore endodontically treated teeth. Endocrowns are full-composite or full ceramic overlays which restore partially or totally the coronal part of a devitalized tooth extending inside the previous pulp chamber (multirooted teeth) or the root canal (single rooted) with a dowel, namely an endo-core. The role of this extension is to stabilize the restoration inside the cavity during the cementation process – more often in case of molars – or to improve its adhesive retention inside the root, typically in severely destroyed premolars and single rooted teeth, depending on quantity and quality of remaining tissues available for adhesion. While for post-retained crown restorations the length of the intra-radicular portion has been widely debated\textsuperscript{16–19} with different results and opinions, few studies exist about the importance of this endo-core and its length over the in-vitro effectiveness of posterior endocrowns\textsuperscript{20–22}. Therefore, the aim of this in-vitro research was to test the influence of the endo-core length on the marginal adaptation, fatigue resistance and fracture mode of ceramic endocrowns to restore severely destroyed upper premolars. Different endo-core lengths were tested for endocrowns and compared to flat overlays (no endo-core, negative control) and to classical post-core-crown
restorations (positive control). Considering both marginal integrity and fatigue resistance of restorations, it was hypothesized that a) endocrowns perform better than flat overlays b) the length of the endo-core has an influence on endocrowns performances and c) endocrowns perform better than crowns.

Materials and methods

Forty-eight freshly extracted human upper first premolars with nearly identical size were used for this study. Bucco-lingual/mesiodistal dimensions and root length of each tooth were measured using digital calipers. The inclusion criteria are absence of carious lesions, visible fracture lines in the root and a complete root formation. The teeth were stored in a sodium azide solution (0.2%) at 4 °C until the experiment onset.

Endodontic procedure

The pulp chamber of all the specimens was opened with diamond burs following a standardized procedure. A size No. 10 K-file (Dentsply-Maillefer, Ballaigues, Switzerland) was placed to visually determine the working length. Then the root canals were prepared using manual K-files 10, 15, 20 (Dentsply-Maillefer) and rotary nickel-titanium instruments (Pro Taper, Dentsply-Maillefer), according to manufacturer’s instructions. 1 mL of 4,2% sodium hypochlorite was used to irrigate root canals during the preparation. All canals were obturated with gutta-percha until the pulp chamber orifice using a warm vertical condensation technique (Calamus, Dentsply Tulsa Dental Specialties, Johnson City, USA). Teeth were then stored in distilled water for 24 h at 4°C before cavity preparation.
Teeth preparation

Each specimen was fixed on a metallic holder (Baltec, Balzer, Liechtenstein) – in a vertical position – with light-curing composite; then, the root base was embedded with self-curing acrylic resin until 1 mm below the cemento-enamel junction (CEJ) to complete the tooth stabilization. For the first three Groups (n = 36), the crown of each tooth was completely cut and flattened till the CEJ. Enamel was completely removed. The roots were then randomly assigned to three Groups (n = 12): in the first Group A, roots were left with the pulp chamber filled of gutta-percha while for Groups B and C, gutta-percha was removed from the pulp chamber until 2 mm (Group B) and 4 mm (Group C) below the CEJ. For the control Group D (n = 12), the crown of each tooth was cut 1 mm above the CEJ and gutta-percha was removed from the pulp chamber and inside the palatal root canal until 5 mm below the CEJ. The outer limits of the teeth of Group D were then prepared with a chamfer (1-mm width, 1-mm high) to create a dentin core and a “ferule” effect. Enamel was completely removed. All these procedures were accomplished using coarse diamond coated burs (Cerinlay, Intensiv, Viganello, Switzerland) and finished with fine grained burs of the same shape under profuse water spray cooling. Then, the cavity dentin surfaces of all specimens were sealed with a layer of an adhesive system (Adhese Universal, Ivoclar-Vivadent, Schaan, Liechtenstein) used in a self-etch procedure according to manufacturer recommendations. The bonding resin was polymerized for 10 s with a second generation LED high-power device (Bluephase, Ivoclar-Vivadent). After the dentin sealing procedure, cavities of Groups A, B, and C were optically impressed (Cerec Omnicam, Sirona, Germany) and then coated with a water-based glycerin gel (Airblock, DeTrey-Dentsply, Constance, Germany) before they were provisionally restored with a soft light-curing resin (Telio CS Onlay, Ivoclar-Vivadent) and kept in saline for 7 days at 32 °C. For teeth of Group D, a pre-calibrated glassfiber post (FRC Postec Plus, Ivoclar-Vivadent) was inserted in the palatal canal and luted with an universal dual-curing resin cement (Multilink Automix, Ivoclar-Vivadent) following manufacturer recommendations. A 4-mm high
core was then fabricated with a restorative nano-hybrid resin composite (Tetric EvoCeram, Ivoclar-Vivadent). Digital impressions (Cerec, Omnicam) were taken and root cavities were provisionally restored as Groups A, B and C.

**Endocrowns and crowns fabrication**

All root cavities were restored with lithium disilicate reinforced CAD-CAM ceramic material (IPS e.max CAD, Ivoclar-Vivadent) and divided in four Groups (n = 12) as shown in Table 4.1: Group A (negative control): flat CAD-CAM overlays with no endocore. Group B: CAD-CAM endocrowns with a 2-mm high endo-core. Group C: CAD-CAM endocrowns with a 4-mm high endo-core. Group D (positive control): conventional CAD-CAM crowns. Before teeth preparation, one of the extracted maxillary first premolar was chosen as a master model. An optical impression of the crown was used to fabricate the crown anatomy of the CAD-CAM restorations using the software Cerec 4.0 in Biogeneric Copy Design mode.

**Luting procedures**

The internal surfaces of all ceramic restorations were etched with 5% HF acid (IPS Ceramic Etching Gel, Ivoclar-Vivadent) for 20 s following manufacturer’s instructions, rinsed and dried. Etched surfaces were cleaned in an ultrasonic bath for 2 min. A layer of silane agent (Monobond Plus, Ivoclar-Vivadent) was applied over the surfaces for 60 s and then air-dried. Root cavities (Groups A–C) and the core preparations (Group D) were submitted to airborne-particle abrasion with 27 μm alluminum oxide particles at about 0.2 MPa pressure for 5 s (Kavo EWL, Type 5423, Biberach, Germany), rinsed with profused water and dried. The silane agent (Monobond Plus, Ivoclar-Vivadent) was then applied on all the sandblasted surfaces (Fig. 4.1). A thin layer of dual-curing resin cement (Multilink Automix, Ivoclar-Vivadent) was spread over the preparation of all specimens. CAD-CAM restorations were then put in place first with manual pressure and then with the assistance of a specific ultra-sonic device (Cementation tip, EMS, Nyon, CH). After removal of excesses, each restoration surface was light-cured for 90 s. Restorations were then
immediately finished and polished, using fine diamonds burs (first 40 μm, then 25 μm grain size) (Intensiv No 4205L, 4255, 5205L and 5255, Intensiv) and discs of decreasing grain size (Pop On XT, 3 M, St. Paul, MN, USA), from coarse (80 μm) to superfine (20 μm). Materials used in the study are shown in Table 4.2.

Table 4.1: The experimental design of the study. Restorations of Groups A–C were 5.5-mm thick from the mesio-distal sulcus to the CEJ (without the endo-core for Groups B and C). Crowns had a thickness of 1.5 mm from the mesiodistal sulcus to the resin core. The inner core of specimens of Group D was 4-mm high from the CEJ included 1 mm of ferrula. CEJ: Cement-Enamel Junction.

<table>
<thead>
<tr>
<th>Group</th>
<th>Maxillary First Premolars (n =12)</th>
<th>Maxillary First Premolars (n =12)</th>
<th>Maxillary First Premolars (n =12)</th>
<th>Maxillary First Premolars (n =12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesive System</td>
<td>Adhese Universal</td>
<td>Adhese Universal</td>
<td>Adhese Universal</td>
<td>Adhese Universal</td>
</tr>
<tr>
<td>Luting Cement</td>
<td>Multilink Automix</td>
<td>Multilink Automix</td>
<td>Multilink Automix</td>
<td>Multilink Automix</td>
</tr>
<tr>
<td>Restoration</td>
<td>e.max CAD</td>
<td>e.max CAD</td>
<td>e.max CAD</td>
<td>e.max CAD</td>
</tr>
<tr>
<td>Endo-core (from CEJ)</td>
<td>0 mm</td>
<td>2 mm</td>
<td>4 mm</td>
<td>post (5 mm) and core (3.5 mm)</td>
</tr>
</tbody>
</table>

Thermo-mechanical fatigue loading

After 24 h the stress test was carried out with an established thermomechanical fatigue method, in a chewing simulator for Thermal Cycling and Mechanical Loading (TCML). All specimens were subjected to 600,000 cycles with 49N axial occusal loading force applied with a ball (diameter of 4 mm) on the buccal cusp at a 1.7 Hz frequency following a one-half sine wave curve. Dimensions of the
indenter were limited by the peculiar occlusal anatomy of the upper premolars, which presents a small inter-cuspal angle. By having the specimen holder mounted on a hard rubber disc, a sliding movement of the tooth is produced between the first contact on an inclined plane of the buccal cusp (mesial or distal) and the central fossa (Fig. 4.1). A total of 1500 thermo-cycles (5°C to 50°C to 5°C) were performed simultaneously.

![Figure 4.1](image)

**Figure 4.1:** A schematic representation of (a) the sliding movement imposed to specimens’ buccal cusp in the chewing simulator during the thermo-mechanical cyclic loading (TCML) and (b) the isometric stepwise cyclic loading test. (c) The different loading contacts are schematically represented in this occlusal view. The positioning of the contacts might slightly vary among the specimens. CEJ: Cement-Enamel Junction.

**Marginal analysis**

Before the TCML test, as well as after completion of the loading phase, gold sputtered epoxy resin replicas (Epofix, Struers, Rødovre, Denmark) are made from polyvinylsiloxane impressions (President light, Coltène, Altstätten, Switzerland). The following interfaces are observed: the restoration cement (RC) interface and the cement-dentin (CD) interface. These two interfaces are analyzed semi-quantitatively by scanning electron microscopy (SEM) (Digital SEM XL20, Philips, Eindhoven, Netherlands) by employing an established evaluation method. The margins are observed at a standard 200× magnification or when necessary for assessment accuracy, higher magnifications up to 1000× can be used. The following evaluation
criteria are tentatively considered: perfect adaptation (continuity), overfilling, underfilling, marginal opening, restoration or tooth fracture. Results for the marginal adaptation, before and following the loading phase, are expressed as percentages of “perfect adaptation” (defect free) for both CD and RC interfaces. Percentages were calculated as the ratio between the cumulative distance of all segments showing the same morphological quality and the whole interface length.

**Stepwise fatigue loading**

After the TCML test all specimens were subjected to a cyclic loading test with an MTS Mini Bionix 858.02 servo-hydraulic testing system (Mini Bionix II, MTS, Eden Prairie, MN, USA) according to a stepwise loading method. The system was equipped with a load cell with a range of 0–2500 N. The chewing cycle was simulated by an isometric contraction. The loading member was a stainless steel ball (diameter of 4 mm). Dimensions of the indenter were limited by the peculiar occlusal anatomy of the upper premolars, which presents a small inter-cuspal angle. Fatigue testing was carried out with unidirectional axial force and under water. Because of the standardized anatomy, all restorations were adjusted in the same position with the loading sphere contacting both buccal and palatal cusps, halfway of the slope (Fig. 4.1). The load varied sinusoidally between a nominal peak value F and 10% of this value (R = 0.1). The loading frequency was 5 Hz. The first 5000 cycles were a warm-up load at 200 N, followed by stages at 400, 600, 800, 1000 and 1200 N of a maximum of 20000 cycles each. Specimens were loaded until fracture or to a maximum of 105000 cycles and the number of endured cycles was registered. The integrity of the specimens was monitored throughout the test with a peak detector (Peak/Valley detector, MTS) which recognizes the difference between current loading and prescribed loading curve. The deviation was usually connected with excessive wear, accidental movements and first micro fractures inside the restoration.
**Fractography**

After fracture all the specimens were visually examined in order to establish which fragments were suitable for fractographic analysis. The first examination of the broken specimens was performed using a stereomicroscope (SZX9, Olympus optical Co. LTD, Tokyo, Japan). Characteristic features like compression curl, hackle and arrest lines were identified. Different magnifications (ranging from 6.3× to 50×) were used depending on the size of the characteristic marks detected. Angled illumination was used to better view the fracture surface. All recognizable features were photographed and documented. Scanning Electron Microscopy (SEM) (Digital SEM XL20, Philips, Amsterdam, Netherlands) was then used for a more detailed analysis of the fractured surfaces. In order to remove all of the impurities, all fragments were cleaned in an ultrasonic 10% sodium hypochlorite bath for 3 min, rinsed with water, dried and then fixed on the support for the microscope. The specimens were gold coated prior to the analysis with the SEM. Magnifications up to 2000× were used to obtain higher definition of identified crack features in selected areas of interest. The overall direction of crack propagation and failure origin(s) were systematically mapped for all specimens. The modes of fracture were analyzed by optical stereo microscopy and classified as (1) catastrophic fracture, propagating to the root, under the CEJ or (2) non-catastrophic fracture, over the CEJ. Classification was based on an agreement between three examiners.

**Statistical analysis**

**Marginal adaptation**

Data and statistical analyses were performed with R software, version 2.15.2 (R Foundation for Statistical Computing, Vienna, Austria). Marginal adaptation, expressed as percentages, was the primary outcome while the technique of restoration (group A to D) and the fatigue (before/after) were the tested independent factors. Because of the low sample size in each group (n = 12) and data
of the primary outcome were not normally distributed (normality was assessed using a graphical tool, QQ plot), differences of marginal adaptation before and after fatigue were assessed using paired Wilcoxon tests. For the same reasons, differences of marginal adaptation between types of method were assessed using Kruskal Wallis tests. In case of significant differences of marginal adaptation between types of method, post-hoc tests were applied for pairwise multiple comparisons using the Nemenyi’s test. Statistical significance was assessed at the two-tailed 0.05 level for all analyses.

*Stepwise fatigue loading*

Comparisons of the fatigue failure responses of specimens were achieved via survival analysis techniques, specifically via Kaplan-Meier product limit estimation (OriginPro 8). Kaplan-Meier product limit estimation, and mean survival times were obtained separately for the four groups (A–D). Plots of survivor functions for each group were obtained. Log rank method was applied as test of the equality of survival times across groups. Percentiles of the survival function (with upper and lower confidence limit) were estimated for the four groups. Alpha level was set at 0.05.
### Table 4.2: Severely damaged endodontically treated teeth: endocrowns

<table>
<thead>
<tr>
<th>Chairside Preparation</th>
<th>Application Mode</th>
<th>Cerec Crown Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>93.5% (524)</td>
<td>Chairside (C)</td>
<td>100% (24)</td>
</tr>
<tr>
<td>94.1% (524)</td>
<td>Chairside (C)</td>
<td>100% (24)</td>
</tr>
<tr>
<td>95.2% (524)</td>
<td>Chairside (C)</td>
<td>100% (24)</td>
</tr>
<tr>
<td>96.3% (524)</td>
<td>Chairside (C)</td>
<td>100% (24)</td>
</tr>
<tr>
<td>97.5% (524)</td>
<td>Chairside (C)</td>
<td>100% (24)</td>
</tr>
</tbody>
</table>

Summary of the products used in the study.
**Results**

*Marginal adaptation*

All the specimens survived the TCLM test except four specimens of Group A (negative control) which showed premature failures during the first 200000 cycles (the exact number of cycles to failure was not determined) due to an early debonding of the restorations (Fig. 4.2).

**Figure 4.2:** SEM analysis of one of the prematurely debonded overlays of Group A.  
(a) Frontal view of the inner intaglio surface of the ceramic restoration (R).  
(b) Lateral view of the margin. The restoration-cement (RC) interface is clearly visible. At low magnification (28×) loss of continuity of this interface is already detectable (white arrow). The integrity of the resin cement (C) is disrupted by an unintentional void (white star).  
(c) Higher magnification (200×) of the adhesive interface. Bonding resin is visible underneath the cement layer (B). Failure can be classified as purely adhesive, between bonding resin and dentin. The polished dentin surface (1200 grit) is impressed over the resin surface (white lines).

For each specimen, the percentage of Continuous (closed) Margin (CM) was calculated for the two interfaces, Restoration-Cement (RC) and Cement- Dentin (CD),
Severely damaged endodontically treated teeth: endocrowns

before and after the loading in the chewing machine. For the four early failed specimens of Group A, a percentage of closed margins equal to 0 after the fatigue test was considered, both for RC and CD interfaces. The results and statistical analysis are shown in Table 4.3 and Fig. 4.3.
Table 4.3: Results of marginal adaptation expressed as Median and interquartile percentage ranges of perfect adaptation for the four Groups (n =12), before and after loading.

<table>
<thead>
<tr>
<th>Restoration-Cement</th>
<th>Cement-Dentin</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group A</strong></td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>86 [84; 91]</td>
</tr>
<tr>
<td>After</td>
<td>68 [0; 80]</td>
</tr>
<tr>
<td>Diff (Af-Be)</td>
<td>-10 [-86; -3]</td>
</tr>
<tr>
<td>pval</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><strong>Group B</strong></td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>82 [75; 88]</td>
</tr>
<tr>
<td>After</td>
<td>66 [60; 81]</td>
</tr>
<tr>
<td>Diff (Af-Be)</td>
<td>-12 [-15; -9]</td>
</tr>
<tr>
<td>pval</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><strong>Group C</strong></td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>90 [88; 93]</td>
</tr>
<tr>
<td>After</td>
<td>79 [64; 85]</td>
</tr>
<tr>
<td>Diff (Af-Be)</td>
<td>-10 [-22; -4]</td>
</tr>
<tr>
<td>pval</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td><strong>Group D</strong></td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>89 [87; 91]</td>
</tr>
<tr>
<td>After</td>
<td>80 [78; 83]</td>
</tr>
<tr>
<td>Diff (Af-Be)</td>
<td>-8 [-13; -5]</td>
</tr>
<tr>
<td>pval</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

Data are median [25th percentile; 75th percentile].
pval\(^1\): Kruskal-Wallis test.
pval\(^2\): Wilcoxon paired test.
Capital letters in parentheses represent the group(s) with which the concerned group is different according to the Nemenyi’s test.
\(\dagger\): in Group A, four specimens failed before the end of the test. A percentage of closed margins equal to 0 "after" the test was considered for them, either for RC and CD interfaces, being early failures distributed between both interfaces. When these failed specimens were not considered for Medians calculation, the eight survived specimens of Group A showed Median values of marginal continuity after the TCML test of 80 [70;82] (interface RC) and 56 [50;64] (interface CD). These values were not statistically compared to values of Groups B-D.

Table 4.4. Pairwise post hoc comparisons with log rank test and medians for survival time.

<table>
<thead>
<tr>
<th>Log rank test</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Medians for survival time (95% confidence intervals)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>p = 0.985</td>
<td>p = 0.704</td>
<td>p = 0.357</td>
<td>A</td>
</tr>
<tr>
<td>B</td>
<td>p = 0.985</td>
<td>-</td>
<td>p = 0.849</td>
<td>p = 0.161</td>
<td>B</td>
</tr>
<tr>
<td>C</td>
<td>p = 0.704</td>
<td>p = 0.849</td>
<td>-</td>
<td>p = 0.070</td>
<td>C</td>
</tr>
<tr>
<td>D</td>
<td>p = 0.357</td>
<td>p = 0.161</td>
<td>p = 0.070</td>
<td>-</td>
<td>D</td>
</tr>
</tbody>
</table>
Figure 4.3: Box-and-whiskers plots indicating percentages of “closed margins” for the four Groups, before and after TCML fatigue loading.

In both interfaces and for all the experimental groups, the percentage values of perfect marginal adaptation after loading were always significantly lower than before loading (pval<sup>2</sup> < 0.001 for all Groups at both interfaces and pval<sup>2</sup> = 0.001 at CD interface of Group C). Considering the RC interface, none of the marginal adaptation before and after the loading was significantly different between the experimental groups (pval<sup>1</sup> = 0.108 before, pval<sup>1</sup> = 0.209 after). Also, the experimented techniques showed no significant influence on the difference of pre- and post-loading marginal adaptation (pval<sup>1</sup> = 0.804). For the interface between the cement and the tooth dentin (CD), the percentage values of closed margins before and after loading were statistically different and inferior between Group A and the Groups B and D (pval<sup>1</sup> < 0.001). According to the Nemenyi's test, no difference was found within endocrowns of Groups B and C and crowns of Group D. The lowest median value of closed margins after the TCML test was found for Group A and a significant difference was found in this column between Group A and Groups B and D (pval<sup>1</sup> < 0.001).
**Stepwise fatigue loading**

After the TCML test, four specimens of the Group A showed premature failure. In the survived specimens of all Groups, no damage such as chip or fissure was detected at the stereomicroscope over the specimens' surface. After the stepwise fatigue test, restorations which survived the 105000 cycles were 4 (50%) in Group A, 6 (50%) in Group C, 5 (42%) in Group B, and 3 (25%) in Group D. All specimens survived until 45000 cycles (the end of 600N stage) (Fig. 4.4).

![Figure 4.4: Kaplan-Meier plotted survival curves of the experimental groups.](image)

Differences in survival between the groups were not statistically significant (p > 0.05) (Table 4.4). The non-overlapping confidence intervals in Table 4.4 give evidence for higher medians for B and C compared to A and D. All restorations experienced non-reparable fractures. Though, different fracture paths were observed (Table 4.5): all fractured specimens of Groups A–C broke with a mesio-distal vertical fracture which split the restoration. Most of these wedge-opening fractures (3 on 4 in Group A, 6/7 in B and 5/6 in C) progressed also in the tooth provoking drastic root breakdowns.
Almost the totality of fractured specimens (8 on 9) of Group D displayed catastrophic fractures in multiple pieces. Fractographic analysis revealed that in all fractured restorations the origin of the fracture was always at the occlusal surface, mainly from the major contact loading area underneath the loading ball of the stepwise fatigue test, and propagated corono-apically (Figs. 4.5 and 4.6).

**Table 4.5:** Types of macroscopic failure for the experimental groups. CEJ: Cement-Enamel Junction.

<table>
<thead>
<tr>
<th>Fractured</th>
<th>Survived</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic (under the CEJ)</td>
<td>Non-catastrophic (over the CEJ)</td>
</tr>
<tr>
<td>Group A (n = 8)</td>
<td>3</td>
</tr>
<tr>
<td>Group B (n = 12)</td>
<td>6</td>
</tr>
<tr>
<td>Group C (n = 12)</td>
<td>5</td>
</tr>
<tr>
<td>Group D (n = 12)</td>
<td>8</td>
</tr>
</tbody>
</table>

CEJ: Cement-Enamel Junction.
Figure 4.5: Group B, fractography of an endocrown restoration.

(a) Stereomicroscope picture from the occlusal view of the reassembled fractured specimen. Two kinds of fatigue damages were detected at the restorations surface, the worn surface over the buccal cusp due to the sliding contact of the TCML (white circle) and two ring surfaces generated by the impact of stepwise loading ball (white stars 1 and 2). The contact 1 was the one that received the highest load (main origin of the crack). White star 3 indicates the origin of the secondary crack, which originated a third minor fragment. This small chip gave to all fractured specimens a typical “y” shape in a sagittal plane.

(b) Schematic representation of the mode of fracture in a sagittal section.

(c) Picture of the fractured surface. The white triangle shows the main origin of the fracture, at the contact point 1. The white arrow shows the track of the stepwise indenter after the primary failure.

(d) Hackle lines are clearly visible in the SEM picture and they indicate the direction of crack propagation (dcp, white arrows).

(e) On the fractured surface of the buccal fragment, the arrest line (dashed white line) represents the limits of the small internal chip.

(f) SEM view of the buccal fragment surface. The white arrows indicate the direction of crack propagation and the white square indicates the end of the crack propagation, turning in a “compression curl”.
Severely damaged endodontically treated teeth: endocrowns

Fig. 4.6: Group D, fractography of a crown restoration.
(a) Stereomicroscope analysis of the fractured surface. The crack started where the indenter of the stepwise test impacted the occlusal surface, then it propagated through the restoration, the resin composite core and the fiber post without any deviation or stop.
(b) In a higher magnification of the impact zone, a void is visible at the interface between cement and the restoration (white pentagon). This flaw generated a concentration of tensile stress during the fracture test that provoked a radial crack (white dashed arrow).
(c) The main origin (white triangle) and the worn surface from the TCML test (white circle) are visible when the specimen is analyzed under the SEM.
(d) A tilted view of the fractured surface in a higher magnification. Hackle lines indicate the direction of crack propagation (dcp, white arrows). Wake hackles (big white arrow) reveal the path of the crack.

Discussion

In the present paper, the impact of an endo-core on marginal integrity and fatigue resistance of premolar endocrowns was evaluated. To the best of authors’ knowledge, a lack of literature exists on this topic. Results of this fatigue test showed that the presence of the endocore has an influence on restorations' marginal integrity, while no effect was evident on their fatigue resistance, meaning that the
hypothesis a) was partially accepted. The length of this endo-core did not seem to have an influence on endocrowns' performances of Groups B and C and, thus, hypothesis b) was rejected. Also, when comparing endocrowns and crowns performances, no difference was found between the experimented groups B and C and the control Group D. Thus, also the hypothesis c) was rejected. Extremely destroyed first upper premolars were used as specimens in this test because endocrowns effectiveness to restore endodontically treated premolars still needs to be proved\textsuperscript{23}. Teeth were cut at the CEJ and flattened to create the worst clinical scenario. In these conditions adhesion of an endocrown is restricted to cervical dentin and the final amount of free available surface for adhesion is limited by pronounced mesio-distal furcations as well as, inside the root, by a pulp chamber of around 4 mm from the CEJ to pulpal floor. A lithium disilicate high-reinforced CAD-CAM ceramic (IPS e.max CAD, Ivoclar-Vivadent) was used for restorations being one of the most common restorative material for single unit crowns and endocrowns\textsuperscript{24}. Restorations were milled from industrially fabricated homogeneous ceramic blocks using the anatomy of an extracted upper premolar as master model. That allowed a high standardization of the specimens in terms of crown dimensions, occlusal anatomy and material properties. Specimens in this in-vitro study were fatigued in two distinct phases. During the first phase, all the restorations were subjected to a thermo-mechanical cycling loading (TMCL) in a computer-controlled chewing simulator. To mimic in-vivo masticatory conditions, the low chewing force of 49 N was applied for 600000 cycles at 1.7 Hz, which corresponds to approximately 2.5 years of mild clinical function (without peaks) in premolar region\textsuperscript{25-27}. A more clinically relevant number of cycles of 106 at low masticatory loads – corresponding to approximately 5 years of function – has been suggested before\textsuperscript{28}. Though, in present study, fatigue conditions were exacerbated later and, moreover, a recent clinical trial on lithium disilicate ceramic posterior crowns reported marginal discontinuity long before 5 years of clinical use\textsuperscript{26,29}. No artificial periodontium was placed around the roots as films normally used for this purpose show degradation.
during the test and their final thickness is not standardizable. This could have negatively affected the results of this in-vitro test as periodontal ligament is a natural shock absorber\textsuperscript{30}. The sliding movement created by the peculiar set-up of this test generated shearing stresses on restorations which are normal for premolars during chewing function. It also exacerbated the testing conditions\textsuperscript{31}. The assessment of the restorations' margins integrity was the main purpose of this first fatigue. It is well known that thermal stresses\textsuperscript{32}, aqueous media\textsuperscript{33} and mechanical occlusal loadings\textsuperscript{34} have a degrading effect on resin bonding interfaces in-vitro, with a good clinical correlation\textsuperscript{35,36}. In particular, lateral movements, such as the ones simulated in this test, are more detrimental than axial ones for adhesive interfaces\textsuperscript{31}. Basing on the fact that an endo-core improves the bonding surface of restorations inside the root as well as their macro-mechanical retention, hindering their displacement from the root cavity under lateral stresses, the presence of this root extension in endocrowns of Groups B and C was supposed to give better results in terms of margins' continuity than flat overlays (Group A), whose retention was purely adhesive. Four specimens (30\%) of Group A gave premature debonding considerably before the conclusion of the fatigue test and this outcome confirmed that assumption. Failure analysis at the SEM of the four debonded surfaces displayed an adhesive loss as major failure mode, mainly localized at the resin-tooth interface (Fig. 4.2). The eight survived specimens of Group A showed good median values of marginal continuity before and after the TCML test when the four failed specimens were not considered for Medians calculation. These values have been inserted separately into Table 4.3. However, the high rate of early debonding in this Group discourages the use of flat overlays with only adhesive retention to restore extremely destroyed premolars. Plus, the adhesive cementation of flat restorations without any retentive form remains in any case a very difficult procedure in clinics and thus not recommended. No differences in marginal continuity were found between endocrowns with short (2 mm – Group B) and medium (4 mm – Group C) endo-cores neither before nor after the TMCL test. Though, degradation of margins (the difference between pre- and post-load values)
in specimens of Group C was clearly higher than that of Group B. That could be explained by the fact that CAD-CAM fabricated endocrowns with deep cavities inside the root can be associated to larger marginal and internal discrepancies between the restoration and the cavity than endocrowns with small endo-cores, due to technical limitations of the optical impression. The resultant high cement film thickness at the interface could be prone to higher degradation under stress. Further studies are needed to confirm this hypothesis. Endocrowns (Groups B and C) and crowns (Group D) showed similar outcomes in terms of marginal continuity. Similar trends were observed in the study of Ramirez et al. where lithium disilicate crowns on central maxillary incisor roots with medium glass-fiber posts (5 mm) were compared to endocrowns with 5 mm endo-cores under the same laboratory testing conditions. IPS e-max restorations were adhesively cemented to premolars' roots with a self-adhesive dual-curing resin cement (Multilink Automix, Ivoclar-Vivadent) associated to a universal primer (Monobond Plus, Ivoclar-Vivadent) as suggested by the fabricant and in agree with a recent independent laboratory study. Results of this first fatigue indicate that the use of these materials to cement lithium disilicate ceramic endocrowns and crowns is efficient in terms of marginal stability and retention on condition that their adhesive performances could be coupled to a macromechanical retention of the restorations into the root to compensate for any stress exerted on adhesive surfaces during chewing. Specimens which survived the TCML fatigue test were then submitted to a stepwise fatigue test. During this second phase, fatigue testing conditions were “accelerated” by mounting stepwise the load as well as the frequency of the cycles. Similar conditions have been already applied in others in-vitro studies. The rationale behind this test was to strengthen the testing conditions to get restoration failure under fatigue conditions, over a certain number of cycles. However, it is important to note that values obtained with this second fatigue (load-to-fracture or cycles-to-fracture values) should not be used to predict the clinical behavior of tested restorations as specimens are submitted to a severe and non-physiological fatigue regimen. Analysis of the plotted Kaplan–Meyer
survival curves shows that none of the groups can offer the longest survival rate (Fig. 4.4). Differences in survival between the groups were not statistically significant (Table 4.4). Though, the non-overlapping confidence intervals in Table 4.4 give evidence for higher medians for B and C (the number of cycles beyond which 50% of the samples are expected to survive) compared to A and D. This indicates a trend to better resistance to fatigue for specimens of Groups B and C. Endocrowns of Groups B and C performed in a very similar way. In Fig. 4.4 their survival curves are almost overlapped and their modes of fracture (Table 4.5) have analogous characteristics. Most of the specimens of these two Groups broke with a mesio-distal vertical fracture which split the restoration and progressed into the root in a catastrophic way (under the CEJ). This kind of wedge-opening fracture was not unexpected as the loading sphere of the stepwise test was in contact with both buccal and palatal cusps, halfway of the occlusal slope. The main crack started from the contact which received the higher amount of load, and then propagated downward rapidly, splitting the restoration with a relatively smooth crack front and provoking drastic root breakdown. Immediately after this first breakdown (primary crack, main origin), the indenter impacted the opposite cusp slightly below the occlusal contact of the stepwise fatigue, producing a secondary crack front. Consequently, a third small fragment was always detectable between the main portions of the primary crack. This chip gave to fracture a typical “y” shape in a sagittal section (Fig. 4.5). Dimensions of this fragment could vary among the specimens but they were always more restricted than the primary crack because of the lower amount of energy available during this secondary impact. Fractographic analysis revealed intense surface and sub-surface fatigue damages where the loading ball of the stepwise test impacted the occlusal surface of the restorations. More details about fractographic analysis of these damages are included in Fig. 4.5. High loads – such as the ones imposed in this stepwise fatigue – concentrated on small occlusal surfaces are known to create consequences localized on the restoration’s surface more than a bulk effect\textsuperscript{43,44}. That could explain analogies in survival and mode of fracture between
endocrowns of Groups B and C, as the only difference between these two groups concerned the length of the endo-core which is localized in the root and far from the occlusal surface. Survival rate of specimens of Group A (flat overlays without endo-core) after the stepwise test was expected to be lower considering their high rate of early debonding (30%) during the TCML fatigue. The peculiar set-up of this fatigue regimen – uniaxial isometric loading concentrated at the restorations' occlusal surface – is more prone to test the mechanical resistance of restorations than their retention and adhesive behavior. The good survival rate of these flat overlays could be an evidence of this predominant effect of axial stresses over shear ones during the stepwise test. Crowns of Group D displayed a survival rate statistically not different to endocrowns of Groups B and C. However, percentiles estimations (Table 4.4) and the slope of the respective curves in Kaplan-Meier chart (Fig. 4.4) suggest a tendency to better fatigue resistance of endocrowns than crowns. It is reasonable to suppose that limited thickness of crowns restorations of Group D (around 1.5 mm at the occlusal isthmus) compare to endocrowns (around 5.5 mm) could be the reason of this lower resistance. An increasing linear relation between thickness and fatigue resistance as well as fracture strength of lithium disilicate reinforced ceramic restorations has been already shown before. It is important to note that the restricted number of specimens per group used in this study could have limited the statistical power in showing any significant difference within these groups. Main mode of fracture of specimens of Group D was a catastrophic failure in multiple pieces. Therefore, fractography of broken specimens was problematic. Though, in few analyzable pieces, origin of the primary crack was localized at the main occlusal contact of the stepwise loading ball and fractography features at the occlusal surface were analogous to wedge-opening fractures of endocrowns described before (Fig. 4.6).
Conclusions

Within the limits of this in-vitro study, fatigued endocrowns with both 2-mm and 4-mm long endo-cores displayed outcomes in terms of marginal integrity and fatigue resistance equivalent to classical crowns. Results of this test discourage the use of flat overlays with only adhesive retention to restore extremely destroyed premolars. Almost the totality of the fractured specimens broke in a catastrophic way, under the CEJ. Further in-vitro studies and clinical trials are needed to confirm these results.
References


