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ORIGINAL ARTICLE

Influence of proximal box elevation on the marginal quality and fracture behavior of root-filled molars restored with CAD/CAM ceramic or composite onlays

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Abstract
Objectives This study investigated the influence of proximal box elevation (PBE) with composite resin when applied to deep proximal defects in root-filled molars with mesio-occluso-distal (MOD) cavities, which were subsequently restored with computer-aided designed/computer-aided manufacturing (CAD/CAM) ceramic or composite restorations.
Materials and method Root canal treatment was performed on 48 human mandibular molars. Standardized MOD cavities were prepared with the distal box located 2 mm below the cemento-enamel junction (CEJ). The teeth were randomly assigned to one of four experimental groups (n=12). In groups G1 and G2, the distal proximal box was elevated up to the level of the CEJ with composite resin (PBE). No elevation was performed in the remaining two groups (G3, G4). CAD/CAM restorations were fabricated with feldspathic ceramic (Vita Mark II, CER) in groups G1 (PBE-CER) and G3 (CER) or with resin nano-ceramic blocks (Lava Ultimate, LAV) in groups G2 (PBE-LAV) and G4 (LAV). Replicas were taken before and after thermomechanical loading (TML; 1.2 Mio cycles; 49 N; 3,000 thermocycles between 50 °C and 5 °C). Following TML, load was applied until failure. Fracture analysis was performed under a stereomicroscope (×16). Marginal quality before and after TML (tooth restoration, composite restoration) was evaluated using scanning electron microscopy (×200).
Results After TML, lower percentages of continuous margins were observed in groups G1–G3 compared with pre-TML assessments; however, the differences were not statistically significant. For group G4-LAV, the marginal quality after TML was significantly better than in any other group. The highest mean fracture value was recorded for group G4. No significant difference was found for this value between the groups with PBE compared with the groups without PBE, regardless of the material used. The specimens restored with ceramic onlays exhibited fractures that were mainly restricted to the restoration while, in teeth restored with composite onlays, the percentage of catastrophic failures (fractures beyond bone level) was increased.
Conclusion PBE had no impact on either the marginal integrity or the fracture behavior of root canal-treated mandibular molars restored with feldspathic ceramic onlays. CAD/CAM-fabricated composite onlays were more favorable than ceramic onlays in terms of both marginal quality and fracture resistance, particularly in specimens without PBE.
Clinical relevance Composite onlays with or without PBE may be a viable approach for the restoration of root-filled molars with subgingival MOD cavities.

Keywords Root-filled molars · Subgingival margins · Proximal box elevation · Ceramic onlay · Composite onlay · Fracture resistance · Marginal quality

Introduction

It is well known that endodontically treated teeth (ETT) are prone to fracture [1–3]. Multiple reasons for this tendency

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have been discussed, such as the biomechanical changes that enamel and dentin undergo following endodontic therapy or the loss of substance that occurs during caries removal and cavity preparation [4, 5]. It has been shown that ETT with mesio-occluso-distal (MOD) preparations display maximal tooth fragility [4–6]. Additionally, greater occlusal loads must be applied to ETT versus their vital opposites before perceived pain triggers load release [7, 8]. To increase fracture resistance and protect the remaining tooth structure in extended MOD cavities, a restoration with bonded indirect onlays is suggested following cuspal reduction of at least 1.5 to 2 mm [2, 3, 5, 6, 9].

When proximal defects are located in deep sub-gingival areas, cavity preparation, impression taking, and adhesive cementation under dry conditions can be challenging [10–12]. Furthermore, the marginal integrity of these restorations is difficult to control; cement excesses in the sulci are difficult to detect and remove, and interactions with biologic width may occur. Surgical crown lengthening is commonly indicated to preserve healthy periodontal conditions and sufficient dimensions of the junctional epithelium and the supra-alveolar connective tissue attachment in such cases [13]. A less invasive alternative procedure involves relocating the proximal cavity margin from an intra-crevicular to a supra-gingival position using direct composite techniques before placing an indirect restoration [11, 12, 14–17]. This approach is commonly referred to as proximal box elevation (PBE) and is restricted to the comparatively small subgingival area. While it is challenging to perform an adhesive restoration in this region, PBE as a single procedure is still better controlled, and contamination is more easily avoided with PBE, even when rubber dam placement is not feasible [17]. Certainly, this proximal composite resin box has to be plain, smooth, and accessible for adequate oral hygiene to be maintained.

Upon relocation of the cavity margins to a supra-gingival position, a sufficient rubber dam application with dry conditions needed for adhesive cementation becomes feasible. Moreover, this approach avoids bulky restorations, which significantly reduce the access of curing light in deep cavities [18, 19]. Therefore, PBE may improve light curing and the marginal integrity of indirect restorations. Furthermore, as one of the most critical steps of the cementation procedure, the removal of excess luting composite is better controlled if the margins are relocated supragingivally [14]. The proximal composite base may also reduce the stresses that occur during insertion, polymerization shrinkage, or functional loading [20].

According to recent in vitro studies performed on non-endodontically treated molars, PBE did not necessarily influence the marginal adaptation compared with indirect restorations without the placement of a proximal composite base [11, 12, 21]. However, there are currently no data available regarding how composite bases in deep sub-gingival areas impact the marginal quality and fracture behavior of root canal filled teeth with indirect restorations.

In recent decades, ceramic has become the material of choice for tooth-colored indirect or semi-direct restorations. While the use of ceramic materials may risk the occurrence of brittle fractures, the recently introduced composite resin blocks for computer-aided designed/computer-aided manufacturing (CAD/CAM) restorations have several advantages, including low wear rates, favorable aesthetics, cost effectiveness, optimal stiffness, and an elastic modulus similar to dentin [6, 22, 23]. Furthermore, the fracture resistance of the composite resin blocks is greater than that observed for feldspathic ceramic restorations [23–27]. Finally, a finite element model was used to demonstrate that composite resin onlays reduce stress concentrations in ETT due to their lower modulus of elasticity [6].

The aims of the present study were the following: (1) to investigate whether the placement of composite bases into ETT harboring deep proximal defects influences marginal adaptation and fracture resistance following thermo-mechanical stress in molars with CAD/CAM onlays and (2) to analyze how material choice (ceramics vs. composite blocks) impacts fracture behavior.

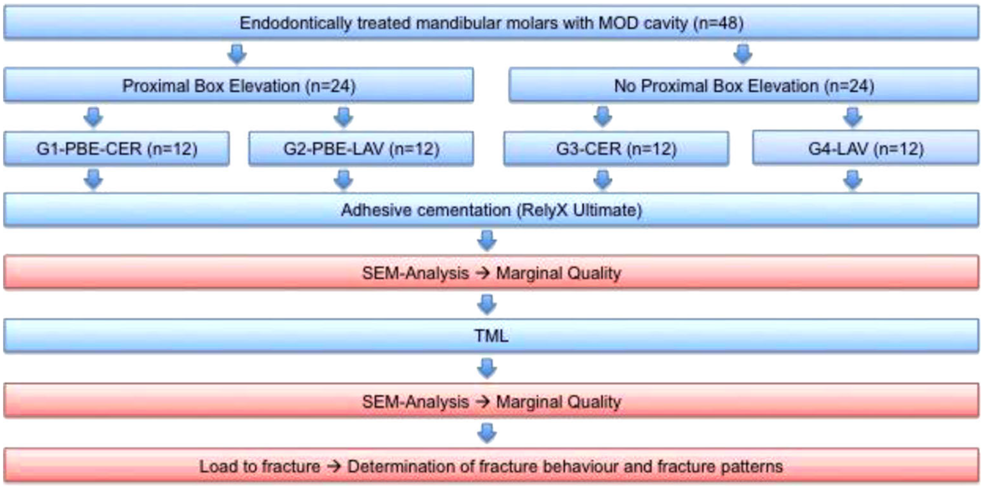
Materials and methods

The study protocol was approved by the local ethics committee (Ethical Committee of Basel, Ref. Nr. EK: 221/12).

Specimen selection and preparation

Forty-eight human mandibular molars with similar dimensions at the cemento-enamel junction (CEJ), but without any evidence of caries or fractures, were cleaned mechanically with scalers and stored in a 0.1 % thymol solution before further processing. All teeth were randomly assigned to one of four experimental groups (G1 to G4, each with $n=12$, Fig. 1). Root canal preparation was performed using rotary instruments (Mtwo, VDW, Munich, Germany) up to an apical size of ISO 40. Sodium hypochlorite (1 %) was used as a root canal irrigant following the use of each instrument. The root canals were filled with vertically condensed gutta-percha (BeeFill, VDW) and an epoxy sealer (AH-Plus®, Dentsply De Trey, Konstanz, Germany). The root canal filling was reduced to a level of 1 mm below the root canal orifice. Water-cooled diamond burs (Inlay-Preparation-Set 4261, Komet, Lemgo, Germany) were used on all specimens to create standardized MOD preparations with an occlusal width of half of the intercuspal dimension. The cervical margins were located mesially 1 mm above the CEJ and distally 2 mm below the CEJ.

Fig. 1 Overview of the study design



In all the teeth, restoration of the endodontic access cavity was performed with composite resin (Tetric EvoCeram, Ivoclar Vivadent, Schaan, Liechtenstein). Additionally, in half of the specimens (n=24), the distal box was elevated with composite up to the level of the CEJ (G1 and G2). No elevation was performed in the remaining 24 specimens (G3 and G4). For surface conditioning, enamel margins and dentin were etched for 30 and 10 s, respectively, with 37 % phosphoric acid (Ultra-etch, Ultradent, Salt Lake City, UT, USA) and rinsed with water for 30 s before being gently dried with air. A three-step etch-and-rinse adhesive (Optibond FL, Kerr, Orange, CA, USA) was applied and light-cured as recommended by the manufacturer. In groups G1 (PBE-CER) and G2 (PBE-LAV), the deep proximal box in the distal aspect of the tooth was filled up to the level of the CEJ with two 1-mm layers of composite (Tetric EvoCeram). Each layer was light-cured separately using a LED curing light (Bluephase G2, Ivoclar Vivadent) for 20 s at 1,200 mW/cm^2. Restoration margins were finished and polished with Sof-Lex discs (3 M ESPE, Seefeld, Germany).

For the onlay preparations, a 2 mm reduction of the buccal and lingual cusps was performed on all teeth. All cavity walls were finished, and sharp inner corners were rounded using a fine diamond bur (4315S, 40 µm; 5,250, 15 µm, Allround-Set Student Set UNI Basel PEK, Intensiv, Grancia, Switzerland). Optical impressions of the onlay preparations were made with an intraoral camera (CEREC Bluecam, Sirona, Bensheim, Germany). For all specimens, onlays were fabricated with the CEREC 3D system (CEREC AC, software package 4.03).

In groups G1 (PBE-CER) and G3 (CER), the onlay fabrication was performed using feldspathic ceramic blocks (Vita Mark II, Vita Zahnfabrik, Bad Säckingen, Germany). The remaining restorations (G2-PBE-LAV and G4-LAV) were manufactured using composite resin blocks (Lava™ Ultimate, 3 M ESPE).

Luting procedure

First, 37 % phosphoric acid gel (Ultra-etch, Ultradent) was applied to the enamel for 15 s before rinsing with water for 10 s. The cavity surface was then gently dried with air for 5 s. A bonding system (Scotchbond Universal Adhesive, 3 M Espe) was applied for 20 s using micro-brushes (Micro-Brush plus, 3 M Espe). To avoid generating any detrimental effects to the fit of the restoration, the adhesive was thinned for 5 s with air to control film thickness. Afterwards, the tooth surfaces were light-cured for 20 s using a light curing unit set at 1,200 mW/cm^2 (Bluephase G2, Ivoclar Vivadent).

The internal surfaces of the ceramic onlays (G1-PBE-CER and G3-CER) were etched with 9.5 % hydrofluoric acid (Porcelain Etch, Ultradent) for 60 s, rinsed with water for 15 s, and dried with air for 20 s. The intaglio surfaces of the composite restorations (G2-PBE-LAV and G4-LAV) were silicatized (Cojet System, 3 M Espe). The bonding system (Scotchbond Universal Adhesive, 3 M Espe) was then applied to all 48 internal surfaces for 20 s and dried with air for 5 s without light curing. The onlays were cemented with RelyX Ultimate (3 M Espe). Under continuous pressure, excess luting material was removed with a polyurethane foam pellet (Pele Tim®, Voco GmbH, Cuxhaven, Germany). To prevent the formation of an oxygen-inhibited layer, the restoration margins were covered with a water-based glycerine-gel (Airblock, DeTrey-Dentsply). Light curing was performed from the mesial, distal, buccal, lingual, and occlusal directions for 20 s each at 1,200 mW/cm^2 (Bluephase G2). The restorations were finished with diamond burs (4,205 L, Intensiv) and polishing discs (Soflex) under an operating microscope at a magnification of ×10 (OPMI pico, Carl Zeiss, Oberkochen, Germany).

Thermomechanical loading (TML)

The roots of all specimens were coated with a 0.3-mm gum resin layer (Anti-Rutsch-Lack, Wenko-Wenselaar, Hilden, Germany) to simulate a periodontal ligament. The roots were subsequently embedded in self-curing acrylic resin (Demotec 20, Demotec Siegfried Demel, Nidderau, Germany) such that the restoration margins were located approximately 3 mm above the feigned bone level.

All specimens were loaded with repeated thermal and mechanical stress using a computer-controlled masticator (CoCoM 2, PPK, Zürich, Switzerland) for 1.2 Mio cycles with 49 N at 1.7 Hz with cusps of human molars as antagonists. Thermal stress was applied simultaneously via 3,000 thermocycles between 5 °C and 50 °C. These conditions are considered to simulate approximately 5 years of clinical service [28].

Load to fracture

To determine the fracture behavior and fracture patterns of the samples, all specimens were tested using a universal testing machine (Zwick, Ulm, Germany). Specimens were fixed in a metal holder, and a 6-mm diameter steel sphere was positioned on the central fossa at an angle of 15° relative to the long axis of the tooth. To avoid excessive stress concentrations at the tooth surface, aluminum foil (0.5-mm thickness) was placed between the onlay surface and the steel sphere. The load was applied at a cross-head speed of 0.5 mm/min until failure.

Fracture analysis

All specimens were meticulously examined under a stereomicroscope (Wild-Heerbrugg AG, Heerbrugg, Switzerland) at a magnification of ×16 to obtain a detailed failure analysis. The fracture lines of each specimen were identified and categorized into three patterns: (1) fractures affecting solely the restoration, (2) fractures affecting both the restoration and the tooth above the simulated bone level, and (3) fractures affecting both the restoration and the tooth below the feigned bone level. The latter failure type was judged to be non-restorable, while categories 1 and 2 were deemed to be restorable fracture modes. Each specimen was investigated from five sides (buccal, lingual, mesial, distal, and occlusal), and any visible fracture line was illustrated on a schematic according to its direction and position.

Quantitative marginal analysis

Pre- and post-TML crown impressions were made using polyvinyl-siloxane (President light body, Coltène, Altstätten, Switzerland), and epoxy resin replicas (Stycast 1266, Emerson & Cuming, Westerlo, Belgium) were fabricated and sputter-coated with gold (Sputer SCD 030, Balzers Union, Balzers, Liechtenstein). A quantitative marginal analysis was performed on the distal box of each specimen by an experienced examiner using a scanning electron microscope (Amray 1810/T, Amray, Bedford, MA) set at 10 kV and ×200 magnification.

Marginal integrity was evaluated at two different interfaces (Fig. 2). The first interface (“tooth–composite”) was located between the cervical tooth structure and the composite margin (either the material used for PBE or the luting composite in groups without PBE). The second interface was located between the ceramic/composite onlay and the luting composite (“onlay–luting composite”). The marginal quality was classified as “continuous” (no gap), “non-continuous” (gap or interruption of continuity, fractures related to restoration margins), and “not judgeable/artifact.” Finally, the percentage of

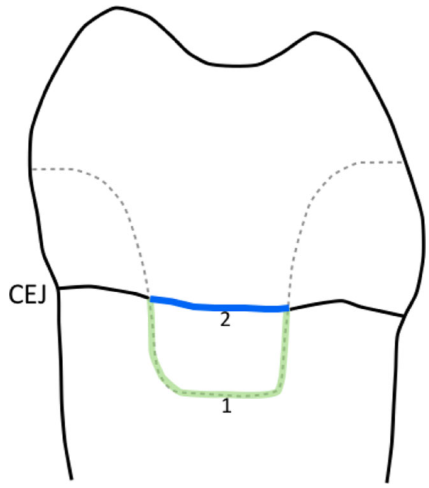


Fig. 2 Interfaces evaluated for marginal integrity Interface 1: Tooth–composite (*green line*) between the cervical tooth structure and the composite material used for the elevation of the proximal box (G1 and G2) or the luting composite (G3 and G4). Interface 2: Onlay–luting composite (*blue line*) between the ceramic/composite onlay and the luting composite (G1 and G2)

Table 1 Percentage of continuous margins at the interface tooth–composite before and after TML

Group	Before TML		After TML	
	Mean	95 % CI	Mean	95 % CI
G1-PBE-CER	81.4 C	72.7; 90.1	64.6 C	46.6; 82.6
G2-PBE-LAV	91.9 BC	87.7; 96.1	80.1 C	67.9; 92.2
G3-CER	81.6 C	72.9; 90.3	69.8 C	61.4; 78.1
G4-LAV	97.5 AB	95.7; 99.2	98.4 A	97.2; 99.6

A significant difference between two groups exists when the confidence intervals do not overlap. Groups indicated with the same letter were not significantly different

Table 2 Percentage of continuous margins at the interface onlay–luting composite before and after TML

Group	Before TML		After TML	
	Mean	95 % CI	Mean	95 % CI
G1-PBE-CER	89.5 A	79.1; 100	46.9 B	31.3; 62.6
G2-PBE-LAV	98.5 A	97.7; 99.4	95.2 A	91.8; 98.6

A significant difference between two groups exists when the confidence intervals do not overlap. Groups indicated with the same letter were not significantly different

continuous margin within each specimen was calculated and presented as a percentage of the individual judgeable margin.

Statistical analysis

Statistical evaluation was performed with JMP 9 software (SAS Institute, Cary, NC, USA). Descriptive statistical calculations were performed to generate means and standard deviation. The data from the fracture resistance tests were graphically displayed as box-and-whisker plots. The fracture loads were investigated by one-way analysis of variance followed by multiple comparisons using Tukey's post hoc test. Values of $p<0.05$ were accepted as statistically significant.

Mean values and confidence intervals were calculated for the marginal adaptation scores in each group. Groups were considered significantly different when the confidence intervals did not overlap.

Results

Marginal quality

Prior to TML, a significantly higher percentage of continuous margins were detected in G4-LAV compared with G1-PBE-CER and G3-CER at the "tooth–composite" interface (Table 1). After TML, lower percentages of continuous margins were observed in groups G1, G2, and G3 compared with the pre-TML assessment, but these differences were not statistically significant. In group G4 (LAV), the marginal quality after TML was significantly better than that measured for any other group but did not differ from the pre-TML assessment.

A significant reduction in marginal quality was detected at the "onlay–luting composite" interface following TML in specimens restored with ceramic onlays (G1-PBE-CER), while no significant difference was observed for teeth restored with composite onlays (G2-PBE-LAV, Table 2).

TML and load-to-fracture test

The highest mean fracture value was recorded for G4-LAV and was significantly different from that recorded for G3-CER ($p=0.0053$). Groups G1 and G2, which had undergone proximal box elevation, revealed similar values regardless of the material used (Fig. 3).

Specimens restored with ceramic onlays (G1 and G3) predominantly exhibited fractures solely within the restoration while, in teeth restored with composite onlays (G2 and G4), the percentage of catastrophic failures increased. In groups G1, G2 (with PBE), and G4 (no PBE), all fractures on the distal aspect of the tooth had a vertical orientation while, in group G3, horizontal fractures of the ceramic restoration at the level of the cuspal reduction were observed in 4 out of 12 specimens (Table 3; Fig. 4).

Discussion

This study was conducted to investigate how PBE and the use of different restoration materials influence the marginal adaptation and fracture behavior of root-filled molars with MOD cavities. It was demonstrated that PBE did not impact fracture resistance regardless of the material used. Overall, composite restorations exhibited better

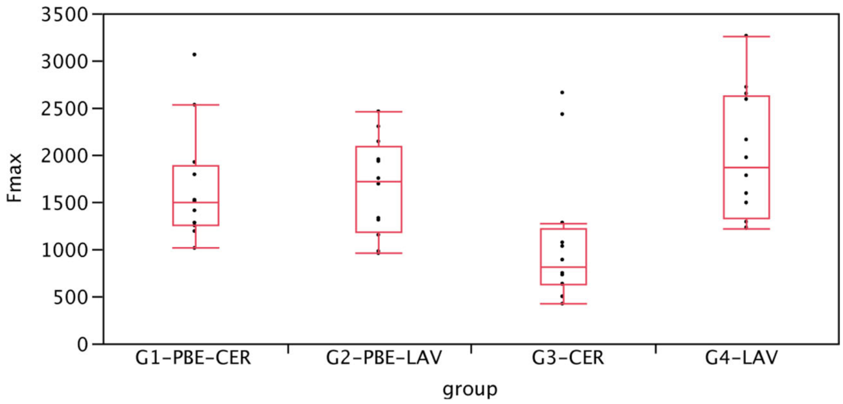


Fig. 3 Box-and-whisker plots of the fracture load for each group (in Newtons)

Table 3 Results of the load-to-fracture test in the four experimental groups: mean load capability values in *N*, standard deviation (SD), confidence intervals (CI), and fracture modes

Groups	Mean (SD)	95 % CI	Fracture mode 1 (within the restoration)	Fracture mode 2 (restoration and tooth, above bone level)	Fracture mode 3 (catastrophic; below bone level)
G1-PBE-CER	1,664.2 (594.5) AB	1,286.5; 2,041.9	10	1	1
G2-PBE-LAV	1,661.8 (513.7) AB	1,335.4; 1,988.1	7	2	3
G3-CER	1,083.0 (727.7) B	620.6; 1,545.4	10	0	2
G4-LAV	1,995.8 (679.9) A	1,563.8; 2,427.8	4	2	6

Groups indicated with the same letter were not significantly different

marginal integrity and higher fracture resistance compared with ceramic onlays.

In the current study, the relocation of deep cavity margins was performed using two layers of a bonded hybrid composite resin based on the results of a recently published study, which demonstrated that a meticulous layering technique with a hybrid material is the best way to counteract gap formation [11]. The concept of coronal relocation of cavity margins extending cervically into the dentin structure was first proposed by Dietschi and Spreafico [14] to simplify the clinical procedure of adhesive cementation. Different materials such as resin-modified glass ionomers, compomers, and flowable composites were considered for use in this approach.

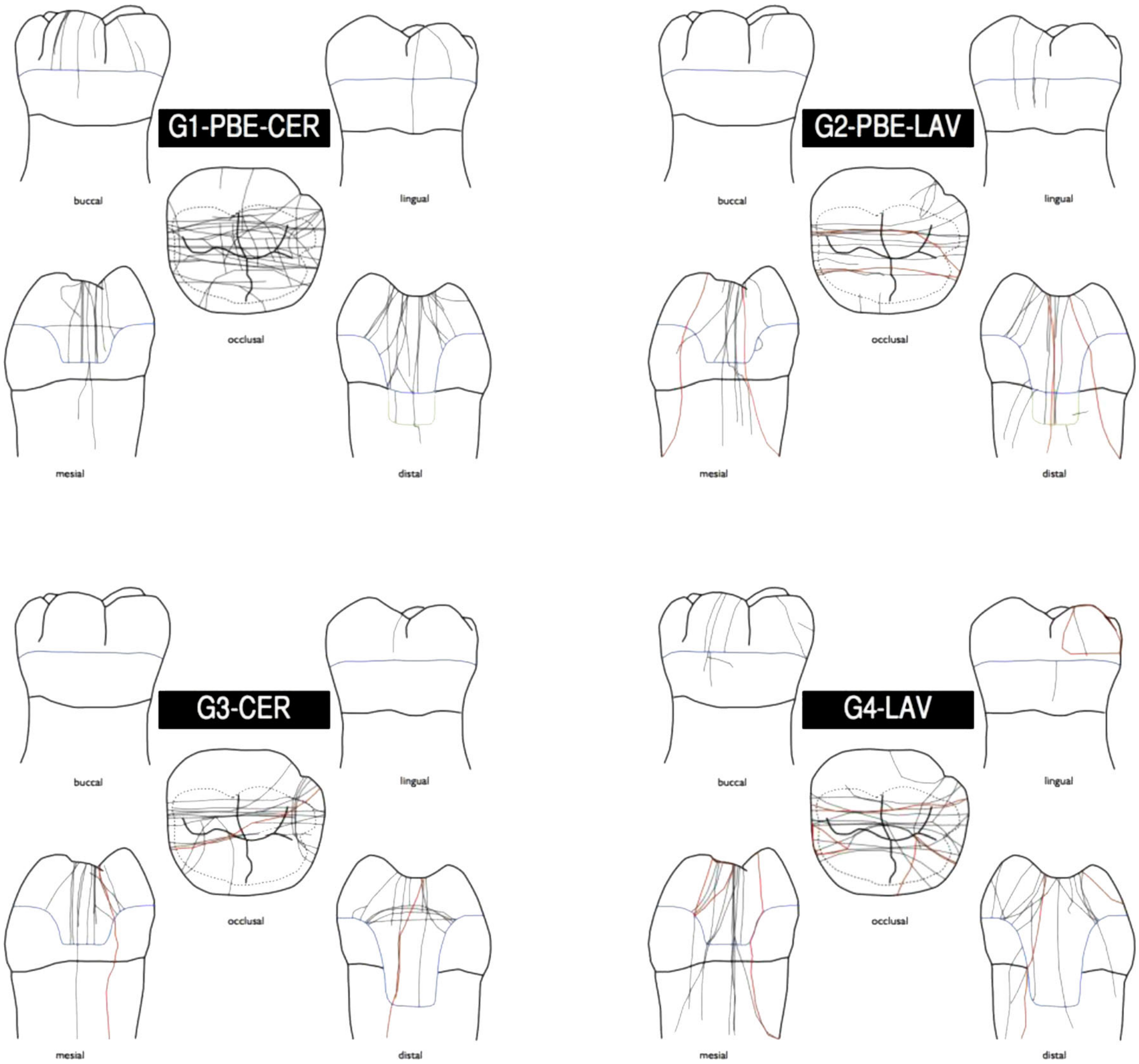


Fig. 4 Detailed failure modes of each experimental group, summarizing the main fractures (*red lines*) and cracks (*black lines*)

Controversy exists regarding whether material properties can influence marginal and internal adaptation in the area surrounding PBE. Dietschi et al. [10] found that materials with an intermediate elastic modulus such as flowable composites had a more favorable marginal adaptation compared with rigid materials, while Rocca et al. [21] found that composite type exerted no significant influence on marginal adaptation. Furthermore, the application of three consecutive 1-mm-thick layers of a highly filled restorative composite provided the best marginal quality to dentin, whereas self-adhesive resin cements performed significantly more poorly [11]. In accordance with these results, a recent study discussed the benefit of highly filled composites for PBE due to their lower contraction stress during polymerization and higher resistance to deformation under load compared with materials with a lower modulus of elasticity [12].

In the present study, teeth with composite onlay restorations and PBE showed a poorer marginal integrity at the dentin interface following TML compared with specimens without PBE. PBE was not found to influence the marginal quality of the specimens restored with ceramic onlays, while fracture resistance seemed to be slightly increased (though this increase was found to be insignificant). Accordingly, other studies have shown that the PBE approach has no adverse effect on the marginal integrity of dentin [11, 12]. The increased fracture resistance is most likely related to the reduced extension of the proximal wing causing different stress patterns on the restored tooth [29]. Among the ceramic specimens, PBE led to vertical fracture lines only, while restorations without PBE exhibited horizontal fracturing of the distal proximal wing at the level of the cuspal coverage. These findings may be due to a combination of an unfavorable cavity design with a greater concentration of tensile stress at the transition between the occlusal and proximal boxes and the rigidity of the ceramic material.

Overall, the present results revealed a considerably greater percentage of perfect margins at both interfaces and higher fracture resistance for composite onlays compared with feldspathic ceramic restorations. These findings are in accordance with previous data comparing the two materials [6, 24, 30–32]. The marginal adaption of crowns fabricated from composite blocks was found to be better compared with ceramic crowns in endodontically treated teeth [33]. Obviously, the higher resilience of the composite material attenuates the stress transferred to the restoration margins. Composite resins possess mechanical characteristics similar to dentin that might reduce the stress generated in the residual hard tissue [6]. Lin et al. [24] showed that large ceramic restorations exhibit higher stress levels and that the use of materials with a lower elastic modulus like composite resins limits the stress intensity transmitted to the remaining tooth structure. Another current study showed that composite resin restorations produced the most favorable stress distribution pattern in MOD cavity restorations of both vital and endodontically treated teeth [6].

The present study demonstrated that the type of material used to restore teeth influenced the proportion of catastrophic versus repairable fractures. The latter were more frequent among the specimens restored with ceramic onlays and were located within the restoration in the majority of cases. This is in agreement with previous data showing that teeth restored with feldspathic ceramic tend to have less severe fractures that do not involve the tooth structure itself, in contrast to bonded composite restorations [34]. Ceramic restorations tend to concentrate more stress inside the restoration whereas composite resins transfer more stress to the tooth structure [35].

In general, extrapolating from in vitro data to draw conclusions regarding the clinical performance of restorations of ETT must be performed with caution. The majority of in vitro studies performed to date have only evaluated the maximum load capability of tooth specimens, and extrapolating the observations made during destructive testing to clinical conclusions is not realistic. Artificial ageing is known to have a considerable impact on the data generated in load-to-fracture tests [36]. For this reason, an experimental design combining cyclic loading within physiological limits and simultaneous thermocycling was used in the present study. Furthermore, the periodontal ligament was simulated to more accurately mimic the oral cavity [37, 38].

Conclusion

PBE does not negatively influence the marginal integrity or fracture behavior of root canal-treated mandibular molars restored with feldspathic ceramic onlays. In particular, CAD/CAM-fabricated composite onlays without PBE are more favorable in terms of marginal quality and fracture resistance than are ceramic restorations.

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Conflict of interest The authors have no conflict of interest related to this study.

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