# Marginal Quality and Fracture Strength of Root-canal Treated Mandibular Molars with Overlay Restorations after Thermocycling and Mechanical Loading

Mustafa Dere[a]/Mutlu Özcan[b]/Till N. Göhring[c]

**Purpose:** To evaluate marginal quality, fracture modes, and loads-to-failure of different overlay restorations in root-canal treated molars in a laboratory setup.

**Materials and Methods:** Thirty-two mandibular first molars were randomly assigned to four groups (n = 8): UTR= untreated (control), RCT-COM= root canal treated (RCT)+ lab-made composite overlay, RCT-FRC= RCT+composite resin overlay with two layers of multidirectional woven glass fibers; RCT-CER: RCT+ceramic overlay. The teeth in all groups were subjected to thermocycling and mechanical loading (TCML) in a computer-controlled masticator (1,200,000 loads, 49 N, 1.7 Hz, 3000 temperature cycles of 5°C to 50°C). Marginal adaptation was evaluated before and after TCML with scanning electron microscopy at 200X at the tooth-to-luting composite (IF1) and luting composite-to restoration (IF2) interfaces. After TCML, all specimens were loaded to failure in a universal testing machine at 0.5 mm/min. Data were analyzed with ANOVA and Bonferroni correction ($\alpha = 0.05$).

**Results:** Marginal adaptation decreased from 93 ± 3.4 to 82 ± 6.5 % at IF1 after TCML ($p > 0.05$) but the decrease was not significant between the groups ($p > 0.05$). At IF2, ceramic overlays showed about 10% lower marginal adaptation than composite overlays ($p < 0.05$). Loads-to-failure (in N) were as follows in descending order: RCT-FRC: 3619 ± 520; UTR: 3048 ± 905; RCT-COM: 2770 ± 457; RCT-CER 2036 ± 319. RCT-FRC showed significantly higher results than those of RCT-COM ($p < 0.05$) and RCT-CER ($p < 0.05$). Only RCT-CER showed significantly lower results than that of the control ($p < 0.05$). While the fractures in the UTR occurred exclusively above the cementoenamel junction (Mode 1 and Mode 2) and were rated reparable, RCT-COM and RCT-CER showed exclusively catastrophic failures in varying modes (nodes 3 to 5). Only in group RCT-FRC, half of the specimens fractured in a reparable fracture mode (modes 1 and 2) with veneering composite delamination from the glass-fiber weaver layer.

**Conclusion:** As cusp-covering overlay restorations in root canal treated molars, composite resin overlays with and without fiber reinforcement performed similar to intact teeth with varying failure types. While intact teeth failed exclusively in reparable modes, all other restorations failed in a catastrophic manner, except half of the fiber reinforced composite group.

**Keywords:** ceramic, composite resin, cusp-covering restoration, fiber reinforced composite, fracture resistance, marginal adaptation, overlay, root-canal treated teeth.

*J Adhes Dent 2010, 12: 287-294.*
*doi: 10.3290/j.jad.a17711*

*Submitted for publication: 19.05.08; accepted for publication: 15.05.09.*

A common method of restoring a tooth after root canal treatment is a coronal-radicular buildup and a subsequent cast restoration.[32] When a large quantity of intact tooth structure is present, using the adhesive systems makes a more conservative and defect-oriented restorative technique possible today. On the other hand, intracoronal restorations may not be able to bear the same load as an undamaged tooth,[18] even if sophisticated adhesive techniques are used.[19] More than 20-year-old clinical data[33] and results from a retrospective clinical study indicated a higher medium- to long-term survival rate for crowned root-canal treated teeth vs non-crowned ones.[1] Yet the preparation of a full coverage crown often poses new problems on such teeth; the last remnants of coronal dental hard tissues around the endodontic access cavity may be lost, which could compromise retention of the full coverage crown. In most of the root-canal treated teeth, the use of root canal posts is thought to be necessary, which again may weaken the root and might put the tooth at risk for operational errors.[23,28] Moreover, no sig-

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[a] *Associate Dentist, Clinic of Preventive Dentistry, Periodontology and Cariology, Center for Dental and Oral Medicine, University of Zürich, Switzerland.*

[b] *Professor, Clinic for Fixed and Removable Prosthodontics and Dental Material Science, Center for Dental and Oral Medicine, University of Zurich, Switzerland.*

[c] *Senior Lecturer, Clinic of Preventive Dentistry, Periodontology and Cariology, Center for Dental and Oral Medicine, University of Zürich, Switzerland.*

***Correspondence:*** *PD Dr.med.dent. Till N. Göhring, Clinic for Preventive Dentistry, Periodontology and Cariology, Center for Dental and Oral Medicine, University of Zürich, Plattenstrasse 11, CH-8032 Zurich, Switzerland. Tel: +41-44-634-34-70, Fax:+41-43-211-33-22. e-mail: till.goehring@zzmk.uzh.ch*

**Table 1 Experimental groups and the materials used in this study**

| Group | n | Adhesive | Restorative material | Reinforcement | Luting material |
|---|---|---|---|---|---|
| UTR | 8 | – | – | – | – |
| RCT-COM | 8 | Syntac[1] | Composite (Tetric Ceram[1]) | – | Composite (Tetric[1]) |
| RCT-FRC | 8 | Syntac[1] | Composite (Tetric Ceram[1]) | Glass fibers (Vectris Frame[1]) | Composite (Tetric[1]) |
| RCT-CER | 8 | Syntac[1] | Ceramic (ProCad[1]) | – | Composite (Tetric[1]) |

[1] Ivoclar Vivadent; Schaan, Liechtenstein
UTR = untreated; RCT-COM= RCT+lab-made composite overlay restoration; RCT-FRC= RCT+lab-made composite resin overlay with two layers of multidirectional woven glass fibers; RCT-CER= RCT+ceramic overlay.

nificant beneficial effect from a root canal post could be expected on the success rate of root canal treated molars.[30] The full coverage crown margins are usually in close proximity to the marginal periodontium. As a consequence, negative gingival reactions were described as well as an increased susceptibility to secondary caries in this demanding oral-hygiene area.[20,30,31]

In fact, the main goal of dental treatment should be to preserve what remains rather than to replace what is lost. Hence, if an intracoronal restoration does not lead to sufficient fracture resistance in root-canal treated teeth, the next step should be to slightly reduce the occlusal cusps and cover them with a restorative material.[9] Overlays (synonyms: onlays or partial crowns) should stabilize the compromised tooth by preventing occlusal forces spreading from cusps and reaching the vulnerable areas of the tooth.[9] With cusp-covering overlays, much more dental hard tissue can be conserved than in the case of full coverage crowns. With this approach, root canal post placement becomes unnecessary and restoration margins can be kept away from the delicate marginal periodontium. In addition, onlays have been found more likely than inlays to restore the compressive fracture resistance of the tooth.[3,6]

Tooth-colored cusp-covering restorations can be accomplished using ceramics, composite resins, and fiber-reinforced composites. These materials are more likely to fulfill today's patient's demand for imperceptible restorations than well-established amalgam or cast metal overlays. Especially glass-fiber- and polyethylene-fiber-reinforced composite resin overlays were found to resist high loads-to-failure together and possess more favorable (reparable) failure modes.[3,5]

Glass fibers have significantly higher flexural strengths than do composite resins.[16] When they are placed in areas with high tensile stresses, they are able to reinforce a restorative composite resin significantly.[16] Composite resin overlay restorations could be produced employing a direct application technique, a semi-direct technique, or an indirect technique in the dental laboratory on a plaster cast.[29] Fiber-reinforced composite resin restorations could in principle be produced in the same manner. However, the intraoral application of fibers has some difficulties. Hence, their fabrication on a plaster cast with an antagonistic cast seems to be more appropriate.

For ceramic inlays and overlays, chairside CAD/CAM techniques as well as laboratory techniques have been described.[25] Several benefits were described for chairside CAD/CAM fabrication of ceramic inlays. The industrially optimized ceramic blocks possess better structural homogeneity and fracture strength than laboratory processed dental ceramic materials.[33] Additionally, restorations can be constructed and fabricated in the same appointment as the cavity preparation and the root canal obturation.[4,25] This is desirable to minimize the risk of tooth fractures or root canal reinfection during the provisional restoration phase.[4]

Although the cavity configuration factor (C-factor) of overlay cavities is smaller than that of mesio-occlusal-distal cavities,[8] little information is available on marginal adaptation of these restorations.[7] Furthermore, marginal adaptation and mechanical properties of such overlay restorations after thermomechanical loading is not known. The objectives of this study therefore were to analyze the marginal quality, evaluate the level of load-to-failures, and modes of failures of various adhesive overlay restorations and to compare the outcome with intact human molars. It was hypothesized that (1) marginal adaptation of all kinds of adhesive overlay restorations would be comparable and (2) fracture resistance would increase with incorporation of glass fiber layers.

## MATERIALS AND METHODS

For this study, 32 extracted mandibular first molars of comparable dimensions were selected by visual inspection, digital caliper measurement (CAPA 150, Tesa; Renens, Switzerland) and radiographs (Digora, Soredex; Helsinki, Finland). Twenty-four molars were randomly divided into four experimental groups of eight teeth each. Experimental groups and the materials used in this study are listed in Table 1. The remaining eight caries-free mandibular first molars were used as controls, that is, they were not prepared at all (UTR). In all groups, the teeth had radiographically visible root canals, no cervical or root caries, and possessed similar dimensions measured at the cementoenamel junction. Teeth with extremely curved roots and wide or atypically shaped root canals were excluded. All teeth were stored in 0.1 M thymol solution from extraction until treatment. The patients had been informed before extraction that their teeth would be used for research purposes. The extraction had no influence on the individual treatment plans of the patients. All teeth were cleaned with scalers, nylon bristle brushes and pumice. The roots of all teeth were covered with an air-thinned 0.3-mm layer of polyvinylsiloxane (President light, surface activated, Coltène Whaledent; Altstätten, Switzerland) to simulate a periodontal ligament. They were then centrally mounted on scanning electron microscopy (SEM) specimen carriers (Balzers Union; Balzers, Liechtenstein) with autopolymerized resin (Paladur, Heraeus Kulzer; Hanau, Germany) with a centering device (PPK; Zurich, Switzerland). The distance between the cementoenamel junction and the resin was 3 mm to simulate the biological width.

### *Root Canal Treatment*

While the teeth in the UTR group were not endodontically treated, in the remaining four groups, all teeth were. After access cavity preparation with a high-speed contra-angled handpiece (Sirius; Micro-Mega; Besancon, France) and a diamond bur (FG 8514, Intensiv; Grancia, Switzerland), a step-down procedure was performed using Gates Glidden burs (sizes 3 to 1; Maillefer; Ballaigues, Switzerland) in a low-speed contra-angled handpiece (Micro-Mega) for the first 3 mm. Nickel-titanium files (#20; NitiFlex, Maillefer) were inserted, and the working length was assessed with digital x-rays (Digora). Root canal preparation was performed with machine driven rotary files (Profile .04, Dentsply; Konstanz, Germany) and EDTA glide solution (RC Prep Endodontic Lubricant, Stone Pharmaceuticals; Philadelphia, PA, USA). The master apical rotary instrument was #35 in mesial and #45 in distal canals. After each file, the canal was rinsed with sodium hypochlorite (1% wt). Following root canal preparation, the canals were rinsed with 17% EDTA (Pulpdent; Watertown, MA, USA), dried with paper points (Dr. Wild & Co; Basel, Switzerland) and obturated using cold lateral condensation with gutta-percha points (#35) in mesial and in distal canals (#45) (Roeko; Langenau, Germany), accessory point size A (Roeko), and a sealer (AH-Plus; Dentsply). The access cavities were covered with a temporary restorative (Cavit, 3M ESPE, Seefeld; Germany) and the teeth were stored in tap water at 36°C for at least 24 h.

### *Cavity Preparation*

In groups RCT-COM, RTC-FRC and RTC-CER standardized non-beveled mesio-occluso-distal (MOD) cavities with one proximal cervical finishing line located in the dentin and another in the enamel were initially prepared with coarse diamond burs (100 µm; FG8614, Intensiv) under water cooling. All remnants of the pulp chamber roof were removed. Additionally, the buccal and palatal cusps were occlusally reduced by 1.5 mm. A 1-mm-deep and 1-mm-wide shoulder finish line was prepared (Fig 1). No liners or bases were used to establish adhesion to all inner cavity surfaces. Cavities were finished with finishing burs (25 µm; FG3614, Intensiv) and the proximal boxes were finished with ultrasonic tips (PCS-Set and Master Piezon 400, EMS; Nyon, Switzerland). After finishing, all finishing lines were located in the dental hard tissues and all cavities had similar dimensions (Fig 1). Impressions of preparations were made with polyvinylsiloxane (President Plus, Coltène Whaledent) in groups RTC-COM and RTC-FRC, and casts were produced (Fujirock, GC; Tokyo, Japan). For RCT-COM, composite resin (Tetric Ceram, A3, Lot F09945, Ivoclar Vivadent; Schaan, Liechtenstein) inlays were made where increments were photopolymerized separately for 60 s (Optilux 500, standard light tip, Demetron Kerr; Danbury, CT, USA).

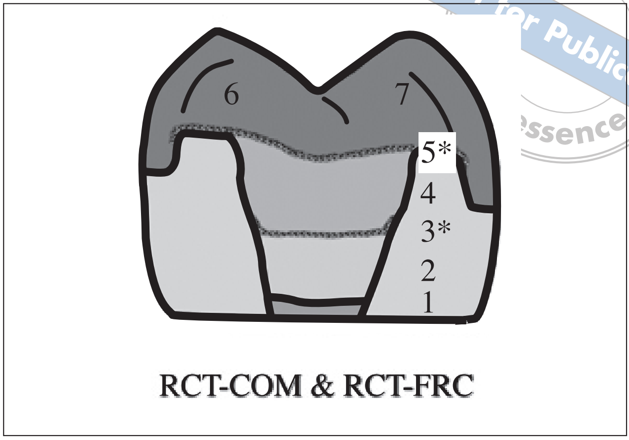


**Fig 1** Overlay preparation design (all test groups) and incremental buildup of RCT-COM and RCT-FRC. Interproximal walls of the Class II cavities with reduced cusps were restored with three composite resin increments. In RCT-COM, the resulting deep Class I cavities were filled with three horizontal increments (1,2,4). In RCT-FRC, glass-fiber weavers (Vectris Frame: 3* and 5*) were additionally adapted to the unpolymerized increments 2 and 4. The occlusal surfaces were built up with two increments (6 and 7).

In group RCT-FRC, glass fiber weavers (weavers consist of four layers of loosely woven glass fiber mats in a liquid polymer matrix) (Vectris Frame, Ivoclar) were adapted to the uncured underlying composite resin increment before polymerization (Fig 1). One weaver was placed approximately at the position of the former roof of the pulp chamber and the other one was placed over the reduced buccal and lingual cusps. For optimized adaptation of the glass fibers to the uncured composite resin, a polyethylene foil was used. This layer was photopolymerized for 60 s through the foil. Subsequently, the occlusal surface and cusps were built up with composite resin (Fig 1). The overlays were post-polymerized with light and heat (100°C) in a composite post-curing oven for 25 min (Targis Power, program 1, Ivoclar Vivadent). After try-in, cementation surfaces of RCT-COM and RCT-FRC were air-particle abraded with 50-µm aluminum oxide (Microetcher, Danville Engineering; Danville, CA, USA) according to the manufacturer's instructions.

In RCT-CER group, cavities were brushed with Cerec Liquid (Vita Zahnfabrik; Bad Säckingen, Germany) and covered with a thin layer of titanium dioxide (ProCad Contrast, Ivoclar Vivadent). Optical impressions were made and overlays were constructed (correlation mode, Cerec 3D, Sirona; Bensheim, Germany). The overlays were then milled from leucite-reinforced glass ceramic (ProCad 300 I14B3/B4, Lot 24540, Ivoclar Vivadent). The titanium dioxide was carefully removed with water spray and rotating, water-spray-cooled nylon bristle brushes (Kerr Hawe; Bioggio, Switzerland). After try-in, cementation surfaces were etched with 5% hydrofluoric acid (Vita Ceramic Etch, Vita Zahnfabrik) for 60 s, rinsed and dried thoroughly. A silane was then applied to the etched surfaces (Monobond S, Lot E34242, Ivoclar Vivadent). After 60 s, remaining solvent was evaporated with oil-free air and sub-surfaces were covered with a thin film of adhesive (Heliobond). The overlay was protected from light until insertion.

### *Adhesive Luting Procedures*

To mimic a realistic operative setting, the prepared teeth were placed in a custom-made typodont model (PPK), with adjustable adjacent teeth,[15] during the adhesive luting procedures. In all prepared teeth, enamel was etched for 30 s with 35% phosphoric acid (Ultraetch, Ultradent Products; South Jordan, UT, USA), rinsed for 40 s with water, and dried with oil-free air. The adhesive system (Syntac Primer, Lot F51870; Syntac Adhesive, Lot F57527; Heliobond, Lot F58115; Ivoclar Vivadent) was applied according to the manufacturer's instructions and photopolymerized for 60 s (Optilux 500, standard light tip). Subsequently, composite (Tetric A2, Lot D00163, Ivoclar Vivadent) was carefully adapted to the inner surfaces of the cavities and the overlays were 7/8 inserted with the help of ultrasound (SP-Tip, Piezon Master 400, EMS; Nyon, Switzerland). Surplus was removed with a probe and the overlays were inserted to the end position using ultrasound. Small amounts of surplus were not removed. Composite was polymerized transdentally from the mesiobuccal, distobuccal, disto-lingual, mesiolingual mesio-occlusal, and disto-occlusal for 60 s each (Optilux 500, Turbo light tip, > 1000 MW/cm$^2$, distance < 1 mm).

Contouring, finishing, and polishing procedures were performed under a stereomicroscope (Stemi 1000, Carl Zeiss; Oberkochen, Germany) at 12X magnification. Finishing diamond burs (15 µm and 8 µm), flexible abrasive disks (Sof-Lex, 3M ESPE), and abrasive polishing brushes (Occlubrush, Hawe Neos; Bioggio, Switzerland) were used.

Impressions were made (President Light Body surface-activated impression material; Coltène Whaledent; Altstätten, Switzerland) and filled with epoxy resin (Stycast 1266; Emerson and Cuming; Westerlo, Belgium). These replicas were compared with those made after thermomechanical loading.

Thirty-two palatal cusps from maxillary second molars were used as antagonists. They were placed into the specimen carriers, as described above, and randomly divided into four groups consisting of eight specimens each. After restoration, all specimens and antagonists were stored in tap water at 37°C for two weeks.

### *Loading*

The specimens were loaded mechanically in the center of the occlusal surface in a computer-controlled masticator (CoCoM 2, PPK) with 1.2 million vertical loads of 49 N at 1.7 Hz and 6000 simultaneous cycles of thermal stress at temperatures from 5°C to 50°C. Each thermal cycle took 120 s. Immediately after thermomechanical loading, replicas were made, sputtered with gold for 1 min (Sputter SCD 030, Balzers, Liechtenstein), and the entire restoration margin was examined by scanning electron microscopy (SEM) at 15 kV from a working distance of 17 mm (Amray 1810T, Amray; Bedford, MA, USA). The researcher was trained in the established procedures by an experienced operator, with whom a re-calibration was accomplished for every group. For the evaluation of marginal adaptation, the researcher was blinded to the group membership of each specimen. For this purpose, all specimens were numbered by a third person who was not involved in this study.

Marginal adaptation was assessed for the following characteristics and expressed as a percentage of the total margin length examined at the tooth-to-luting composite (IF1) and luting-composite-to-tooth (IF2): continuous margin (no gap, no interruption to continuity), non-continuous "imperfect" margins (gap due to adhesive or cohesive failure; fracture of the restorative material or fracture of the dental hard tissue related to restoration margins) at 200X magnification. These observations were made in buccal, oral, proximal, and cervical enamel and cervical dentin-restoration areas to identify the most vulnerable areas of the restoration.

After analysis of marginal adaptation, specimens were placed in a custom-made carrier and loaded axially in a universal testing machine (Schenk Trebel; Baden, Switzerland) with a 10-mm steel sphere. The sphere had three-point occlusal contact. A 0.5-mm-thick piece of tin foil between the steel sphere and crown allowed a more equal load distribution and avoided loading peaks on small surface areas (Fino tin layer 0.50, Fino; Bad Bocklet, Germany). The crosshead speed was 0.5 mm/min. Teeth were transilluminated by cold light (Intralux 4000-1, Volpi; Schlieren, Switzerland) during loading to detect visible fractures.

After failure, the fragments were analyzed for the failure mode: "reparable" tooth fracture that might clinically allow a new restoration, and "catastrophic" tooth/root fracture that might necessitate tooth extraction. Classification was based on a two-examiner agreement. Failures were identified mainly in 5 modes: mode 1: superficial cusp chipping; mode 2: complete cusp chipping; mode 3: vertical fracture along the tooth/restoration interface; mode 4: fracture through the restoration and along the tooth/restoration interface; mode 5: two vertical fractures along the tooth/restoration interface.

### *Statistical Analysis*

The data were analyzed for normal distribution and the results of SEM analysis were tested for statistical significance with factorial (between groups) and repeated measure (before and after thermomechanical loading) analysis of variance (ANOVA). Loads-to-failure were compared using one-way ANOVA. Post-hoc comparisons were

**Table 2a Marginal adaptation at tooth-to-luting composite interface before and after thermomechanical loading (TCML) in percent**

| Group | n | Continuous margin (pooled) | | | |
|---|---|---|---|---|---|
| | | Before TCML (Mean ± SD) | Significance* | After TCML (mean ± SD) | Significance* |
| RTC-COM | 8 | 92.6 ± 1.2 | A | 83.0 ± 3.8 | B |
| RTC-FRC | 8 | 91.3 ± 4.6 | A | 80.8 ± 9.8 | B |
| RTC-CER | 8 | 95.1 ± 2.3 | A | 82.0 ± 5.1 | B |

*No statistically significant differences were found in groups with the same letters ($p < 0.05$).

**Table 2b Marginal adaptation at luting composite-to-restoration interface before and after thermomechanical loading (TCML) in percent**

| Group | n | Continuous margin (pooled) | | | |
|---|---|---|---|---|---|
| | | Before TCML (mean ± SD) | Significance* | After TCML (mean ± SD) | Significance* |
| RTC-COM | 8 | 99.1 ± 0.5 | A | 95.2 ± 2.6 | B |
| RTC-FRC | 8 | 99.1 ± 0.6 | A | 96.7 ± 1.4 | B |
| RTC-CER | 8 | 93.2 ± 2.2 | C | 84.0 ± 3.8 | D |

*No statistically significant differences were found in groups with the same letters ($p < 0.05$).

performed with t-tests. The Bonferroni correction was applied for multiple testing. For all statistical analyses, the level of significance was set at 95%.

## RESULTS

All natural teeth and all restorations survived thermomechanical loading in the computer-controlled masticator without loss of retention or visible fractures, and were used for analysis of marginal adaptation and static load test.

Data of the separately assessed interface areas were pooled due to the minimal and nonsignificant differences within each group. Before thermomechanical loading, marginal adaptation of luting composite to tooth in all three restoration groups did not show significant differences ($p > 0.05$) (Table 2a). More than 90% of the IF1 interface was rated continuous. After thermomechanical loading, these values decreased significantly to values of approximately 80% continuous margins ($p < 0.05$). In all groups, marginal adaptation to enamel finishing lines was significantly better than to cervical finishing lines located in dentin. Here, values decreased in all groups to about 40% continuous margins ($p < 0.05$).

At the IF2 interface, marginal adaptation of ceramic overlays was found 10% lower than those of indirect composite restorations (Table 2b) ($p < 0.05$). An influence on marginal adaptation by the presence of glass fibers was not detected ($p > 0.05$).

During the load-to-failure test, first sounds were recorded between 1362 ± 821 N (UTR) and 2446 ± 432 N (RCT-FRC). The values recorded in the RCT-FRC group were significantly higher than in the control group UTR ($p < 0.05$). Loads at first cracks in the RCT-FRC group did not differ from the other restored groups (Table 3). Total failure, indicated by major load drops and visible (by cold light illumination) damage occurred at mean values between 2036 ± 319 N (RCT-CER) and 3619 ± 520 N (RCT-FRC). Mean load values for RCT-FRC were significantly higher than for RCT-COM ($p = 0.0077$) and RCT-CER ($p < 0.0001$). Teeth restored with composite resin with ($p = 0.0636$) and without glass-fiber reinforcement ($p = 0.355$) fractured at values comparable to those of the untreated controls. Only RCT-CER fractured at significantly lower loads than the control UTR ($p = 0.0019$) (Table 3).

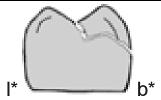
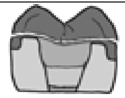
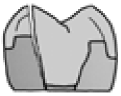
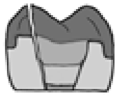
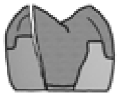
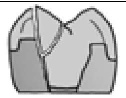
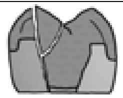
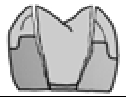
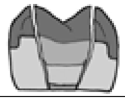
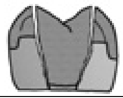
While the fractures in the UTR occurred exclusively above the cementoenamel junction (modes 1 and 2) and were rated reparable, RCT-COM and RCT-CER showed exclusively catastrophic failures of varying modes (modes 3 to 5). Only in group RCT-FRC, half of the specimens fractured in a reparable fracture mode (modes 1 and 2) where the veneering composite was delaminated from the glass-fiber weaver layer (Table 4).

**Table 3 Loads-to-failure and failure characteristics**

| Group | n | Loads-to-failure (N) |  |  |  |  |  | Failure characteristics |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Initial crack |  | Total failure |  |  |  |  |  |
|  |  | Mean ± SD | Significance* | Mean ± SD | Significance* | Minimum | Maximum | Reparable | Catastrophic |
| UTR | 8 | 1362 ± 821 | B | 3048 ± 905 | DE | 1859 | 4298 | 8 | – |
| RCT-COM | 8 | 1942 ± 699 | AB | 2770 ± 457 | CD | 2264 | 3648 | – | 8 |
| RCT-FRC | 8 | 2446 ± 432 | A | 3619 ± 520 | E | 2964 | 4598 | 4 | 4 |
| RCT-CER | 8 | 1800 ± 277 | AB | 2036 ± 319 | AC | 1597 | 2630 | – | 8 |

*No statistically significant differences were found in groups with the same letters ($p < 0.05$).

**Table 4 Types and frequency of failure modes of overlays**

|  | UTR |  | RCT-COM |  | RCT-FRC |  | RCT-CER |  |
|---|---|---|---|---|---|---|---|---|
| **Fracture Modes** | Mode | n | Mode | n | Mode | n | Mode | n |
| **Repairable** |  |  |  |  |  |  |  |  |
| **Mode 1**<br>Superficial cusp-chipping |  | **4** |  | **0** |  | **2** |  | **0** |
| **Mode 2**<br>Complete cusp-chipping |  | **4** |  | **0** |  | **2** |  | **0** |
| **Catastrophic** |  |  |  |  |  |  |  |  |
| **Mode 3**<br>Vertical fracture along the tooth-restoration interface |  | **0** |  | **1** |  | **3** |  | **3** |
| **Mode 4**<br>Fracture through the restoration and along the tooth-restoration interface |  | **0** |  | **3** |  | **0** |  | **1** |
| **Mode 5**<br>Two vertical fractures along the tooth-restoration interface |  | **0** |  | **4** |  | **1** |  | **4** |

*b: buccal, l*:lingual

## DISCUSSION

Fracture resistance of root canal treated molars with different intra- or extra-coronal restorations could be influenced by the restoration type, size of the restoration, and the inherent physical properties of the restorative material affecting the force distribution. With the type of adhesive applications, marginal integrity also becomes an important issue to be considered in the longevity of such restorations.[13] For these reasons, both criteria were considered for the evaluation of restoration options for cuspal-coverage overlay restorations in order to be able to make clinical recommendations.

In marginal integrity, cavity configuration plays a major role. The poor cavity configuration factor of the deep cavities in such teeth may lead to unfavorable marginal adaptation.[8] In this study, adhesive restorations were evaluated where the restorative material covered the buccal and oral cusps for better force distribution. This restoration approach leads to more sound tissue sacrifice compared to intracoronal restorations, but it is still considered a conservative approach as opposed to full-coverage crowns. With overlay restorations, negative effects on the marginal periodontium are avoided or restricted to the proximal boxes.

The favorable marginal quality with overlays could be attributed to the luting cement where a thin film of cement needs to be polymerized. This reduces the cuspal movements through polymerization contraction of the composite.[24] Furthermore, shortening the cusps reduces the cavity configuration factor.[8] Good marginal adaptation before and even after thermomechanical loading with all restoration options could be explained on these grounds. Interestingly, the incorporation of the fibers (81%) in the restoration did not affect the marginal integrity as opposed to the non-reinforced ones (83%). It can be anticipated that the manipulation of the fiber placement could be more restricted in intracoronal applications than with overlays, where more space is available for the fibers. Nonetheless, due to the nonsignificant differences in marginal quality with the adhesive restoration techniques, the first hypothesis was accepted.

Concerning fracture resistance, all teeth restored with overlays achieved values comparable to intact human molars. In particular, the teeth restored with glass-fiber-supported composite resin overlays (RCT-FRC) demonstrated significantly higher load-to-failure values than teeth restored with non-reinforced composite resins (RCT-COM) or leucite-reinforced glass ceramic overlays (RCT-CER), confirming the second hypothesis. Similar findings were reported with polyethylene fiber-reinforced composite overlays compared to non-reinforced ones.[3] Although the fibers used in this study were different than the ones used in the study of Belli et al,[3] this does not seem to influence the load-to-failure values for similar preparations. Determining the effect of fiber type at the interface was not the main objective of this study. However, ultra-high molecular weight polyethylene (UHMWPE) fibers were reported to create inadequate interfacial adhesion to the dental polymers[34] compared to the preimpregnated and silanized glass fibers.[2] The load-bearing capacity of a given construction may be influenced by type of fibers, size, and geometry of the restoration,[20,26] which warrants further research also for overlay restorations. Considering the variations between the effect of fibers in an intracoronal or extracoronal restoration, the question remains to be answered whether the geometry of the preparation or the interfacial reinforcement dominates the load-to-failure and the failure types. Nevertheless, the use of fiber weave in combination with resin composite seems to provide advantages for the overlay restorations.

In a recent study, when woven glass-fiber FRCs were used in combination with overlays, load-to-failure results were not influenced by the FRC application.[11] This could be due to the differences in preparation type. While in that study, palatal cusps were reduced to the cementoenamel junction, simulating amalgam fractures in premolars, this study used molars, and buccal and oral cusps were reduced by only 1.5 mm. When the unsupported composite bulk increases, the load-to-failure may be chiefly influenced by the composite rather than the fiber reinforcement at the interface.[20,26] Finite element analysis also indicated high stress zones at the cervical area of the cusp coverage overlays.[9] Thicker fibers could eliminate catastrophic failures of the supporting veneering composite. In this study, practical considerations led us to apply only one layer of fiber on the roof of the pulp chamber and the other on the reduced buccal and lingual cusps. On the other hand, increased thickness of fibers may lead to exposure at the margins. This could then lead to separation of the resin matrix from the fibers in the saliva.[17] The result is a severe decrease of flexural strength of the restoration and an increased risk for failure.[16] Therefore, thicker layers of glass fibers do not seem applicable.

In general, favorable failure types were noted with the application of the fibers.[9-11,26] Although RCT-FRC was the only group in which half of the overlays survived with minor damage (veneering composite delamination) and a fracture pattern similar to those observed in intact teeth, other kinds of superficial delaminations have been observed clinically with glass-fiber-reinforced composite inlay-retained fixed dental prostheses after two to three years of clinical function.[12] Such failures were not observed in this in vitro setting. Hence, the results should be interpreted with care and controlled clinical trials using this method should be performed and followed up for at least three years.

When thermomechanical loads are applied on the cusps, deflexion-induced separation of the layers could be expected, leading to delamination and eventually catastrophic failure. Therefore, adhesion of each layer, namely the indirect composite, luting cement and the fiber, plays a significant role in the whole assembly. In order to increase the adhesion of the luting cement, overlays were air-particle abraded with 50μ aluminum oxide following the manufacturer's recommendations for luting. Improved adhesion has been reported when prepolymerized composite surfaces were conditioned with tribochemical silica coating and silanization.[27] This aspect needs further investigation.

The leucite-reinforced glass ceramic (ProCad) used in this study is known to be weaker than a recently introduced lithium-disilicate reinforced ceramic.[4] Thus, it could be anticipated that overlay restorations made of this high strength ceramic might result in higher loads-to-failure if tested in the same setup. However, in a recent study, poor marginal adaptation between lithium disilicate ceramic crowns and the luting composite was described.[12] For this reason, future studies should take both marginal quality and the load-to-failure into consideration for the evaluation of intra- or extracoronal restorations.

In the present in vitro study, an attempt was made to simulate aging and material degradation with occlusal loading and thermocycling in a chewing simulator. Although this might be closer to clinical reality than static load testing only, it has its limitations. The direction of the loading may be other than only vertical as it was in this study. Furthermore, load-to failure studies cannot indicate the stresses within the structure.[10,35] The obtained results therefore should be verified using finite element analysis.

## CONCLUSIONS

Within the limitations of this in vitro study on cusp-covering restorations in root canal treated molars with mesio-occlusal-distal Class II cavities, with respect to marginal adaptation and loads-to-failure, it can be concluded that composite resin restorations with and without glass-fiber reinforcement performed similar to intact teeth. Failure types, however, varied between the restorative materials. While intact teeth failed exclusively in reparable modes, all other restorations (except for half of the fiber reinforced composite group) failed in a catastrophic manner.

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**Clinical relevance:** When marginal adaptation and loads-to-failure of lab-made composite overlays, resin composite overlays with two layers of multidirectional woven glass fibers, and ceramic overlays were compared after simulated aging conditions, the results make it possible to suggest all cusp-covering restorations for root-canal treated teeth. The integration of glass fiber layers in the restoration seems to be advantageous, because this yielded loads-to-failure and failure modes similar to those of intact teeth at high static loads.