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Fracture resistance of endodontically treated teeth restored with ceramic inlays and different base materials

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This study evaluated the fracture resistance of endodontically treated teeth restored with different base materials and mesio-occlusal-distal (MOD) ceramic inlays. Fifty mandibular molars were assigned into five groups (n=10 per group). Group1 (control) comprised intact molar teeth without any treatment. Teeth in other groups were subjected to root canal treatment and restored with MOD ceramic inlays on different base materials. In Group 2, base material was zinc phosphate cement; Group 3's was glass ionomer cement; Group 4's was composite resin, and Group 5's was composite resin reinforced with fiber. Finally, a continuous occlusal load was applied until fracture occurred. Mean fracture resistance of Group 1 (3,027 N) was significantly higher than the other groups (890, 1,070, 1,670, 1,226 N respectively). Fracture resistance of Group 4 was statistically comparable with Group 5 and significantly higher than Groups 2 and 3 ($p<0.05$; Tukey's HSD). Use of different base materials under ceramic inlay restorations could affect the fracture resistance of endodontically treated teeth.

Keywords: Composite, Fiber-reinforced composite, Zinc-phosphate, Glass-ionomer, Fracture strength

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INTRODUCTION

When compared with vital teeth, endodontically treated teeth are less resistant to fractures[1-3]. The latter's vulnerability does not arise from differences in the biomechanical properties or moisture content of hard tissues[4,5], but rather due to tooth structure loss which occurs during caries removal and endodontic access cavity preparation. Loss of hard tooth tissue due to endodontic access cavity preparation diminishes the flexural strength of cusps[6]. In addition, pulpless teeth may be more heavily loaded than their vital counterparts before a pain response is triggered, thereby predisposing them to fractures[7]. Intracoronal strengthening of teeth is important to protect them against fractures, particularly in posterior teeth where stresses generated by occlusal loading can lead to fracture of unprotected cusps[1].

Base materials reduce the volume of root canal filling material as well as create the necessary geometry for inlay/onlay restorations[8,9]. The shape of a cavity preparation depends on the extent of decay (caries) and the geometry of the restoration to be placed. Caries removal often creates undesired undercuts, which are not compatible with the principles of cavity preparation designed for inlays/onlays. Therefore, base materials are used under ceramic inlays for these reasons: sealing endodontic access cavities, eliminating undercuts to preserving as much sound enamel/dentin as possible, and providing the proper internal tapered cavity design for ceramic inlay/onlay restorations[9].

After root canal treatment, some studies have suggested reinforcing endodontically treated teeth with ceramic inlays or composite resin restorations[1,10]. However, direct restoration techniques are still plagued by the polymerization shrinkage problem, despite improvements in the physical properties of composite resins[11]. To overcome these shrinkage-related problems, indirect ceramic restorations have been suggested[12].

Fracture remains one of the most common causes of ceramic inlay/onlay failures. Factors that lead to ceramic inlay fractures include inadequate restoration thickness, improper cavity design, deep fissures in the restoration, defects (such as pores and cracks) in the ceramic, and elastic modulus of the base material[12-14]. Aluminous porcelain presents 40–50% more aluminum oxide crystals than feldspathic porcelain, increasing the hardness and reducing the coefficient of thermal expansion. This material is indicated for laminate veneers, inlays/onlays, and as a covering material for porcelain crowns. For all-ceramic crown restorations, their fracture resistance is significantly influenced by the elastic moduli of base materials. Increasing the elastic modulus of the supporting core structure has been suggested as a way to increase the fracture resistance of all-ceramic posterior crown restorations[15,16].

Riding on the developments and advancements in the field of fiber-reinforced polymers, the use of fiber-reinforced composites (FRC) has increased[17]. Various types of fibers, such as glass fiber, polyester fiber, carbon/graphite fiber, aramid fiber (kevlar), and ultra-high molecular weight polyethylene fiber (UHMWPE), have been used with composite materials to improve their

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mechanical properties[17-21]. However, there is a need for more information regarding the effects of different base materials on the fracture resistance of endodontically treated teeth restored with ceramic inlays[22].

This study evaluated the influence of various base materials on the *in vitro* fracture resistance and failure mode of endodontically treated teeth restored with ceramic inlays. The null hypothesis tested was that there would be no significant differences in both fracture resistance and failure mode among the different base materials.

MATERIALS AND METHODS

Tooth specimens

Fifty teeth, freshly extracted due to periodontal reasons, were selected for this study. They were caries-free human mandibular first molars of similar dimensions. Calculus and soft-tissue remnants were removed using a periodontal scaler. The teeth were cleaned using a rubber cup and fine pumice-water slurry, examined to detect any pre-existing defects, and stored in distilled water at room temperature. Roots of teeth were covered with a 0.2-mm layer of polyether impression material (Impregum Garant L DuoSoft, 3M ESPE AG, Seefeld, Germany) to simulate the periodontal ligament (PDL) and embedded in an auto-polymerizing acrylic resin (Meliodent, Heraeus Kulzer, Hanau, Germany) up to 2 mm below the cementoenamel junction[23] (Fig. 1). Artificial tooth mobility was evaluated in the horizontal and vertical dimensions using a Periotest instrument (Periotest, Siemens AG, Bensheim, Germany). Periotest value of the embedded teeth was standardized at a value $\leq +7$ to simulate the natural dentition[24].

Root canal treatment

Teeth were randomly assigned into five groups of 10 teeth each. In Group 1, teeth were not endodontically treated to act as control. For teeth in Groups 2 to 5, access cavity preparation was done using a diamond bur (FG 8514, Intensiv, Grancia, Switzerland) mounted in a high-speed contra-angle handpiece (CA 1:5 L Micro-Series, Bien-Air Dental, Bienne, Switzerland). A step-down procedure for the first 3 mm was performed using Gates-Glidden burs (sizes 3 to 1; Maillefer, Ballaigues, Switzerland) mounted in a low-speed contra-angle handpiece (Sirius, Micro-Mega, Besancon, France). Nickel-titanium file (#20; NitiFlex, Maillefer) was inserted into the root canal, and working length was assessed using digital radiographs (Digora Optime, Soredex, Helsinki, Finland).

Fig. 1 Zinc phosphate cement base material.

Root canal preparation was performed using machine-driven rotary file (Profile .04, Dentsply, Konstanz, Germany) and EDTA glide solution (RC Prep Endodontic Lubricant, Stone Pharmaceuticals, Philadelphia, PA, USA). Master apical rotary instrument was #35 in the mesial canal and #45 in the distal canal for each tooth. 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 canal and #45 in distal canals (Roeko, Langenau, Germany) and a sealer (AH Plus, Dentsply).

Inlay cavity preparation

In all endondontically treated teeth, inlay cavity preparations were made by the same operator using a recommended sequence of specific diamond burs under constant water cooling. Inlay cavities were prepared using a high-speed handpiece (CA 1:5 L Micro-Series, Bien-Air Dental) attached to a parallelometer (Paraskop; Bego; Bremen, Germany) to ensure that all preparations were of a standardized size.

Inlay cavities of rounded internal angles were prepared using 6° tapered diamond burs (Inlay Preparation Set 4261, Komet, Lemgo, Germany). Isthmus floor of mesio-occlusal-distal (MOD) inlay cavities was planned according to the cavity preparation principles for ceramic restorations[25]. Pulpal floor was prepared to a depth of 1.5 mm from the occlusal surface; occlusal isthmus was 1.5 mm wide, and bucco-lingual widths on the mesial and distal boxes were similar to that of occlusal isthmus. Each box had a gingival floor depth of 1.5 mm mesiodistally and an axial wall height of 2 mm. Cavity preparation margins had 90° cavosurface angles.

For Groups 2 to 5, a silicone matrix was fabricated using a putty-type addition-reaction silicone (Aquasil, Dentsply DeTrey, Konstanz, Germany) to replicate the original cavity shape. This matrix was used as a guide to facilitate base placement. Pulpal wall was reduced by an additional 1.0 mm and replaced with the appropriate base material. After curing, excess base material was removed using a fine diamond bur (Inlay Preparation Set 4261, Komet) and an enamel hatchet.

Base placement procedures of Groups 1 to 5 are described as follows:

Group 1 (Control): This group did not receive cavity preparation or root canal treatment; hence no base placement was performed.

Group 2 (ZPC): A zinc phosphate cement (Phosphate Cement, Heraeus Kulzer) was mixed on a glass plate at room temperature. For each portion, 1.2 g of powder was mixed with 0.5 mL of liquid. Cavities were filled, and silicone matrix was applied under finger pressure (Fig. 1).

Group 3 (GIC): Dentin surfaces were conditioned using a cavity conditioner (GC Corp., Tokyo, Japan) for 20 s, rinsed with water for 15 s, and left moist according to manufacturer's recommendations. A resin-modified glass ionomer cement (Fuji II LC, GC Corp., Tokyo, Japan) was mixed according to manufacturer's instructions at 1 scoop of powder with 2 drops of liquid, and then condensed into the cavities. Silicone matrix was applied under finger pressure, and the material was light-cured for 20 s using an LED curing unit (400 mW/cm^2; Elipar Free Light, 3M ESPE Dental Products, St. Paul, USA).

Group 4 (CR): Cavity conditioning was performed using a self-etch adhesive bonding system (Clearfil SE Bond, Kuraray, Tokyo; Japan). Priming agent (SE Primer, Kuraray) was applied for 20 s, and the surfaces were gently dried. Bonding agent (SE Bond, Kuraray) was applied to the cavity surfaces and cured for 10 s. Cavities were restored using a composite resin filling material (Clearfil AP-X, Kuraray) with the bulk filling technique. Silicone matrix was applied under finger pressure, and the material was light-cured for 20 s from each direction using an LED curing unit (Elipar Free Light, 3M ESPE).

Group 5 (CR+Fiber): After performing the priming and bonding procedures as described for Group 4, cavity surfaces were coated with a layer of low-viscosity adhesive resin. Before curing, a piece of polyethylene fiber (4 mm length, 3 mm width) (Ribbond, Ribbond Inc., Seattle, WA, USA) was cut and coated with the adhesive resin. Excess material was removed, and the fiber was embedded in a flowable composite (Protect Liner F, Kuraray) in a buccal-to-lingual direction. After curing for 20 s with an LED curing unit (Elipar Free Light, 3M ESPE), the cavities were restored using a resin composite (Clearfil AP-X, Kuraray) with the bulk fill technique. Silicone matrix was applied under finger pressure, and the material was light-cured for 20 s from each direction using an LED curing unit (Elipar Free Light, 3M ESPE).

Ceramic inlay restorations

Impressions were taken using a polyvinylsiloxane silicone impression material (Elite, Zhermack S.p.A., Badia Polesine, Rovigo, Italy). Definitive dies were fabricated using a refractory die material (Vitadurvest, Vita Zahnfabrik, Bad Sackingen, Germany). Ceramic inlay restorations were manufactured using an aluminous ceramic (Vitadur Alpha, Vita Zahnfabrik) and a refractory mold, with three firings between 600 and 960°C. Intaglio surfaces of ceramic restorations were sandblasted using 50-µm aluminum oxide. Finishing and polishing procedures were carried out using polishing discs (Sof-Lex Pop-On, 3M ESPE), and ceramic restorations were glazed at 930°C.

Bonding procedure

Bonding procedure for the ceramic inlays was performed as follows. The interior surfaces of all specimens were silanized using a porcelain primer (Monobond S, Ivoclar Vivadent AG, Schaan, Liechtenstein) for 60 s and air-dried. A bonding agent (Heliobond, Ivoclar Vivadent AG) was applied to the tooth surfaces and left unpolymerized (to be polymerized after inlay placement). A dual-polymerizing resin cement (Variolink II Base, Ivoclar Vivadent AG) was mixed in equal parts with its catalyst (Variolink II high viscosity, Ivoclar Vivadent AG) for 15 s, applied to the ceramic surface, and light-polymerized after inlay placement. Ceramic specimens were seated perpendicular to the pretreated surface using finger pressure, and excess material was removed using a dental probe. Specimens were light-polymerized with a minimum light intensity of 400 mW/cm^2 (Elipar Free Light, 3M ESPE) for 20 s from each direction. Cement margin was finished using flexible polishing discs (Sof-Lex XT Pop-On, 3M ESPE).

Bonded specimens were subjected to thermal cycling at temperatures of 5°C and 55°C for a total of 5,000 cycles. Dwell time at each temperature was 30 s, and transfer time was 2 s.

Fracture resistance measurement and failure mode analysis

Teeth were subjected to axial compressive loading using

Fig. 2 Positioning and axial compressive loading of specimen in universal testing machine.

a 6-mm-diameter metal sphere applied vertically and centered on the occlusal surface of the restoration at a crosshead speed of 0.5 mm/min in a universal testing machine (TSTM 02500, Elista Ltd., İstanbul, Turkey). To reduce local force peaks, a 0.5-mm-thick foil was inserted between the metal sphere and occlusal surface of restoration. Fracture resistance (N) and mode of failure were recorded (Fig. 2). Mode of failure of each specimen was classified according to Burke *et al.*[26] as follows:

mode I: Isolated fracture of restoration;
mode II: Restoration fracture involved a small tooth portion;
mode III: Fracture involved more than half of the tooth, without periodontal involvement;
mode IV: Fracture with periodontal involvement.

Statistical analysis

Results were analyzed using one-way ANOVA and Tukey's honestly significant difference (HSD) test to determine the presence of statistically significant differences among the groups (p=0.05).

RESULTS

Fracture resistance

Mean and standard deviation values of the fracture resistance of Groups 1 to 5 are shown in Table 1. One-way ANOVA results showed that there were statistically significant differences among the groups (p<0.05). Tukey's HSD test revealed that Group 1 (3,027 N) presented significantly higher fracture resistance than the other groups (p<0.05). Restoration with composite resin base material (Group 4: 1,670 N) also increased the fracture resistance when compared with the other restored groups (p<0.05). Inserting pieces of polyethylene fiber into the composite resin base material (Group 5: 1,226 N) did not increase the fracture resistance when compared with Group 4 (p<0.05). Restoration of endodontically treated teeth with ZPC (Group 2: 890 N) and GIC (Group 3: 1,070 N) before ceramic inlay placement did not improve the fracture resistance when compared with the other groups (p<0.05).

Failure mode

In Group 1 (control), 80% of specimens fractured with failure mode II, with the remaining failures classified as failure mode IV (catastrophic). In Group 2 (ZPC), a higher prevalence of failure mode II (60%) was observed, followed by mode III (20%) and modes I and IV (10% each). In Group 3 (GIC), specimens recorded 50% for failure mode II, followed by 40% for failure mode III and 10% for failure mode I. In Group 4 (CR), 60% of specimens fractured with failure mode III, followed by 40% with failure mode II. For Group 5 (CR+Fiber), 80% of specimens fractured with failure mode II, followed by 20% with failure mode I (Table 2).

Table 1 The mean fracture resistance (N) and standard deviations of each experimental group

Groups	Restoration Type	Fracture Resistance (N)	Standard Deviation (±N)
Group 1	Intact teeth	3,027.45 a	656.93
Group 2	ZPC+inlay	889.98 b	320.12
Group 3	GIC+inlay	1,070.11 b	414.64
Group 4	CR+inlay	1,670.37 c	521.40
Group 5	CR+Fiber+inlay	1,225.63 bc	182.04

Table 2 Mode of fracture of restored specimens according to Burke *et al.*[26]

Mode of Failure	Group 1 Intact teeth	Group 2 ZPC	Group 3 GIC	Group 4 CR	Group 5 CR+Fiber
I	0	1	1	0	2
II	8	6	5	4	8
III	0	2	4	6	0
IV	2	1	0	0	0

mode I isolated fracture of the restoration;
mode II restoration fracture involving a small tooth portion;
mode III fracture involving more than half of the tooth, without periodontal involvement;
mode IV fracture with periodontal involvement.

DISCUSSION

To date, no consensus has been reached in published literature regarding how much fracture resistance is required to achieve long-term success of endodontically treated molars with MOD inlay restorations. Some studies reported that the maximum occlusal bite forces generated during mastication varied between 216 and 847 N[27,28], with the highest bite force recorded in the first molar region[28]. For fixed partial dentures in the posterior region, Körber and Ludwig[29] suggested that they should be able to withstand bite forces of 500 N.

Cyclic fatigue loading from mastication can also considerably weaken dental restorations[30]. In the oral environment, flaws inherent in restorative materials could act as the origin of crack propagation, which could then be exacerbated by cyclic fatigue to develop in a threatening manner[31]. For dental ceramics, endurance limit for fatigue cycling is approximately 50% of the maximum fracture resistance[32]. Therefore, for endodontically treated posterior teeth restored with ceramic inlays, it was reasonable to assume that they need an initial fracture resistance of 1,000 N to achieve favorable clinical outcome.

In the current *in vitro* study, CR group (1,670 N) showed higher fracture resistance than zinc phosphate cement (890 N) and resin-modified glass ionomer cement (1,070 N). These findings agreed with those of previous studies[33,34]. Generally, all-ceramic and composite systems exhibit low resilience and toughness and are vulnerable to fractures[35]. In contrast, fiber-reinforced composite fixed partial dentures were advocated because of these advantages: better adhesion of composite luting agent to the fiber, physiological stiffness of the denture framework made of fiber, and a better elastic modulus match between fiber-reinforced composite restoration and dentin/enamel[36,37].

In the present study, a combination of polyethylene fiber and composite resin did not improve the fracture resistance. The lackluster result could be due to poorly bonded fibers. Improper impregnation of fibers also increases water sorption, leading to a detrimental hydrolytic effect and a decrease in the mechanical properties of the reinforced resin. This finding contradicted that of a previous study[38], in which the use of polyethylene fibers significantly improved the fracture resistance of composite restorations.

Although CR group demonstrated markedly increased fracture resistance when compared with GIC group, restored teeth in both groups demonstrated comparable failure modes. It is also noteworthy that CR group demonstrated a significantly higher number of severe fractures when compared with CR+Fiber group. Therefore, it might be worthwhile to consider using polyethylene fibers to reinforce composite base materials.

In this study, the procedures of fabricating and bonding inlays to extracted human teeth were designed to mimic clinical conditions. Sizes of extracted teeth and dimensions of inlay cavities in each experimental group were also controlled. Cavity standardization was achieved using a paralleling device. This experimental arrangement was set out to reduce operator errors and control occlusal divergence of cavity preparations.

Oral conditions were also simulated in this study. A polyether coating was used to replicate the PDL to simulate physiological tooth movements. Despite the presence of wide variations among human teeth, this PDL simulation method was employed in the current study because fracture resistance is critically dependent on the elastic moduli of abutment materials. Further, abutment mobility is a decisive clinical factor in fracture resistance evaluation: failure is more likely to occur when a small amount of abutment rotation is allowed[39]. One limitation of this study was the non-inclusion of an artificial aging process, such as mechanical loading, which would have mimicked the negative effects of aging on fracture resistance.

CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

1. Restoring endodontically treated first molars with ceramic inlays and a composite base material resulted in higher fracture resistance when compared with zinc phosphate cement and glass ionomer base materials.
2. Placement of polyethylene fiber ribbon into a composite resin in the bucco-lingual direction did not improve the fracture resistance, but resulted in more favorable failure modes.

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