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Fracture Resistance of Teeth Restored With All-ceramic Inlays and Onlays: An In Vitro Study

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Clinical Relevance

In clinical practice, as tooth preparation increases with onlay vs inlay techniques, the fracture resistance of the tooth may decrease depending on the restoration material used.

SUMMARY

Fracture resistance of inlays and onlays may be influenced by the quantity of the dental structure removed and the restorative materials used. The purpose of this *in vitro* study was to evaluate the effects of two different cavity preparation designs and all-ceramic restorative materials on the fracture resistance of the tooth-restoration complex. Fifty mandibular third molar teeth were randomly divided into the following five groups: group 1: intact teeth (control); group 2: inlay preparations, lithium-disilicate glass-ceramic (IPS e.max Press, Ivoclar Vivadent AG, Schaan, Liechtenstein); group 3: inlay preparations, zirconia ceramic (ICE Zirkon, Zirkonzahn SRL, Gais, Italy); group 4: onlay preparations, lithium-disilicate glass-ceramic (IPS e.max Press); and group 5: onlay preparations, zirconia ceramic (ICE Zirkon). The inlay and onlay restorations were adhesively cemented with dual polymerizing resin cement (Variolink II, Ivoclar Vivadent AG). After thermal cycling (5° to 55°C × 5000 cycles), specimens were subjected to a compressive load until fracture at a crosshead speed of 0.5 mm/min. Statistical analyses were performed using one-way analysis of variance and Tukey HSD tests. The fracture strength values were significantly higher in the inlay group (2646.7 ± 360.4) restored with lithium-disilicate glass-ceramic than those of the onlay group (1673.6 ± 677) restored with lithium-disilicate glass-ceramic. The fracture strength values of teeth restored with inlays using zirconia ceramic (2849 ± 328) and onlays with

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zirconia ceramic (2796.3 ± 337.3) were similar to those of the intact teeth (2905.3 ± 398.8). In the IPS e.max Press groups, as the preparation amount was increased (from inlay to onlay preparation), the fracture resistance was decreased. In the ICE Zirkon ceramic groups, the preparation type did not affect the fracture resistance results.

INTRODUCTION

The presence of extensive carious lesions, unsatisfactory restorations, and tooth fractures results in controversy regarding the optimal restorative procedure.[1,2] Indirect restorations have more desirable physical properties than direct composite restorations because they are fabricated under relatively ideal laboratory conditions.[3] When an indirect restoration is determined to be the best treatment option, the clinician must then determine the geometric configuration of the cavity preparation.[1,4,5] Cusp coverage seems to be the most controversial point with respect to the final cavity preparation design for posterior teeth. The mechanical properties of the restorative materials should be considered before choosing the cavity design.[6,7] Cavity preparation is directly related to decrease of cusp stiffness.[8] The depth and width may affect cusp deflection and tooth fracture strength.[9] According to the cusp coverage, the types of restorations can be classified as inlays (no cusp is covered), onlays (at least one cusp is not covered), or overlays (all cusps are covered).[10]

The adhesive technique allows dental professionals to restore the morphology, esthetic appearance, and original mechanical loading capacity of natural teeth.[11,12] The use of ceramics with adhesive techniques permits the preservation of tooth structure and more esthetic restorations in posterior teeth.[13-16] Zirconia is a crystalline dioxide of zirconium. Its mechanical properties are very similar to those of metals, and its color is similar to tooth color. Zirconia crystals can be organized in three different patterns: monoclinic, cubic, and tetragonal.[17] Yttrium-stabilized zirconia, also known as tetragonal zirconia has become available for use in dentistry through computer-aided design/computer-aided manufacturing (CAD/CAM) or copy-milling techniques, and provides excellent mechanical performance, superior strength, and fracture resistance compared to other ceramics.[18,19] However, the use of some types of ceramics remains limited in the posterior region, where extensive masticatory forces are applied.[20,21] In 2005, an improved pressed-ceramic material called IPS e.max Press (Ivoclar Vivadent AG, Schaan, Liechtenstein) was introduced to the market. There are limited data available on IPS e.max Press (Ivoclar Vivadent AG) ceramic. This pressed ceramic is intended to expand the range of applications for IPS Empress 2 (Ivoclar Vivadent AG). While it features similar physical properties to previous materials, its translucency has been improved. The IPS e.max Press (Ivoclar Vivadent AG) system is comprised of high-stability framework material that consists of lithium-disilicate (Li_2O-$2SiO_2$). The restorations can be customized by using either a layering technique based on fluorapatite glass ceramic or by using the staining technique.[22,23]

The parameters for cavity design should be consistent with principles of adaptation, resistance, and retention, occlusion, and esthetics.[1,9,24-26] Adhesive luting procedures can reinforce teeth and minimize deleterious effects of cusp flexure, thus increasing crown stiffness as an outcome of adhesive effects, cohesive resistance, and stress distribution.[6,15,26-28] In *in vitro* studies, a number of factors may interfere with resistance to fracture, such as the tooth embedment method, type of load application device, and crosshead speed.[29-34] Thus, the experimental methods used for *in vitro* analyses do not accurately represent real clinical conditions in which failures occur primarily due to fatigue.[35-38] To minimize the discrepancy between experimental assessments and clinical failures, different methods have been used, such as the joint use of mechanical tests and fracture mode analyses according to predefined scales.[39-44]

The objective of this *in vitro* study was to determine and compare the fracture strength and the failure modes of lithium-disilicate glass-ceramic and yttrium-stabilized zirconia-based ceramic inlay and onlay restorations. The null hypotheses tested were: 1) the preparation type does not affect the fracture resistance of the tooth-restoration complex and 2) the type of restoration material does not affect the fracture resistance of the tooth-restoration complex.

MATERIALS AND METHODS

In this *in vitro* study, 50 freshly extracted, sound, caries-free human mandibular third molars (wisdom teeth) were used. Calculus and soft-tissue deposits were removed with a hand scaler. The teeth were cleaned using a rubber cup and fine pumice water slurry, and examined to detect any preexisting defects. Only intact, noncarious, and unrestored teeth were included in the study. The teeth were stored in distilled water until use, and were removed only during the test procedure. The roots were covered with a 0.2-mm layer of a polyether impression material (Impregum Garant L Duasoft, 3M ESPE AG, Seefeld, Germany) to simulate the periodontal ligament, and embedded in an autopolymerizing acrylic resin (Meliodent, Heraeus Kulzer GmbH, Hanau, Germany) up to 2 mm below the cementoenamel junction. The artificial tooth mobility was evaluated in the horizontal and vertical directions by use of a Periotest instrument (Periotest, Siemens AG, Bensheim, Germany). The Periotest value of the embedded teeth was standardized at a value less than or equal to +7 in order to simulate the natural dentition.[45] The teeth were randomly divided into five experimental groups (n=10) as follows:

- group 1: intact teeth, no treatment (control group) (IT);
- group 2: teeth with inlay restorations with lithium-disilicate glass-ceramic (IPS e.max Press, Ivoclar Vivadent AG) (I-e.max);
- group 3: teeth with inlay restorations with zirconia ceramic (ICE Zirkon Zirkonzahn SRL, Gais, Italy) (I-Zirkon);
- group 4: teeth with onlay restorations with lithium-disilicate glass-ceramic (IPS e.max Press, Ivoclar Vivadent AG) (O-e.max); and
- group 5: teeth with onlay restorations with zirconia ceramic (ICE Zirkon Zirkonzahn SRL) (O-Zirkon).

Using a 6° taper diamond rotary cutting instrument (Inlay Preparations Set 4261, Komet, Lemgo, Germany), two different preparations, with rounded internal angles, were defined. Tooth preparations were made by the same operator (SS) with the recommended sequence of specific diamond burs (Inlay Preparations Set 4261, Komet) under constant water-cooling. To ensure standardized cavity preparations, a parallelometer (Paraskop, Bego, Bremen, Germany) was used. The parallelometer has a milling arm, designed as a multifunctional arm, and a lever for a drilling tool. A motor is integrated in the base for control for the milling unit. The isthmus floor of the mesio-occluso-distal (MOD) inlay cavities was prepared following principles for ceramic and indirect composite resin preparations as described elsewhere.[46] The pulpal floor was prepared to a depth of 2.5 mm from the occlusal surface; the occlusal isthmus was 2.5 mm wide, and buccolingual widths on the mesial and distal boxes were similar to the width of the occlusal isthmus. Each box had a gingival floor depth of 1.5 mm mesiodistally and an axial wall height of 2 mm. Margins were prepared with 90° cavosurface angles. The onlays were prepared using basic techniques, the mesiobuccal and distobuccal cusps were reduced by 2 mm according to the anatomic shape of the occlusal surface, and the buccal margins were finished as 1-mm rounded shoulder design (Figure 1A and 1B).

A two-stage impression was made of each prepared tooth using a polyvinyl siloxane impression material (Elite HD, Zhermack SpA, Badia Polesine, Italy). After 2 hours, the impressions were poured using type IV stone (Durone, Dentsply, Petrópolis, RJ, Brazil). A technician fabricated all restorations using a standardized technique following the manufacturer's instructions. To fabricate the IPS e.max Press (Ivoclar Vivadent AG) restorations, a die spacer was applied to the cavity surfaces at a distance of 1.5 mm away from the marginal areas. The wax frameworks were sprued and invested with a speed investment material (IPS PressVEST Speed, Ivoclar Vivadent AG). A lithium-disilicate glass-ceramic ingot (IPS e.max Press, Ivoclar Vivadent AG) was heated and pressed into an investment mold in the furnace (EP 600, Ivoclar Vivadent AG) after burnout of the wax analog. After divestment with glass polishing beads at 4-bar pressure, fine divestment was performed with glass polishing beads at 2-bar pressure. The pressed frameworks were immersed into 1% hydrofluoric acid (Invex Liquid, Ivoclar Vivadent AG) and cleaned in an ultrasonic cleaner (Whaledent Biosonic Jr, Whaledent International, New York, NY, USA) using distilled water for 15 minutes. After cleaning, the fabricated frameworks were veneered with layering ceramic (IPS e.max Ceram A2 Dentin, Ivoclar Vivadent AG). Analogs of ICE Zirkon (Zirkonzahn SRL) frameworks were fabricated with specific light-polymerizing composite build-up materials (T Rigid, Zirkonzahn SRL). The ICE Zirkon (Zirkonzahn SRL) frameworks were milled in "green" ceramic condition. The frameworks then sintered in a sintering oven (Keramikofen 1500, Zirkonzahn SRL) at 1500°C for 2 hours. The ICE Zirkon (Zirkonzahn SRL) frameworks were veneered with low-fusing ceramic (Ceramic Dentine A2, ICE Ceramic, Zirkonzahn SRL). Completed ceramic restorations were adhesively cemented using a dual-curing fine-particle hybrid composite (high viscosity) (Variolink II, Ivoclar Vivadent AG).

The bonding of the teeth was performed according to the following procedure. The teeth were etched with 35% phosphoric acid (Total Etch, Ivoclar

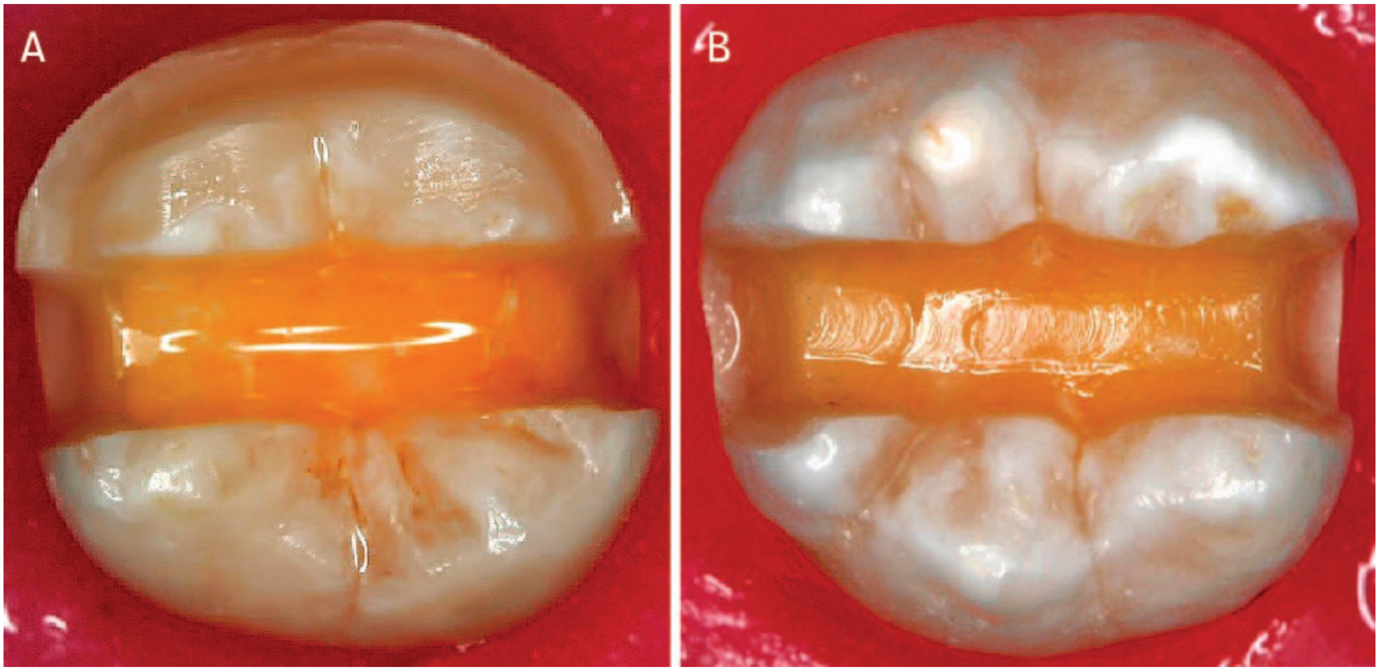

Figure 1. *(A):* Representative onlay preparation. *(B):* Representative inlay preparation.

Vivadent AG) followed by a rinse with water. Excess water was removed in accordance with the wet-bonding technique.[12] Syntac primer (Ivoclar Vivadent AG) was applied for 15 seconds and gently air-dried. Syntac adhesive (Ivoclar Vivadent AG) was applied for 10 seconds and gently air-dried. A bonding agent (Heliobond, Ivoclar Vivadent AG) was applied and left unpolymerized (polymerized together with Variolink II). The same procedure was followed for each tooth.

The bonding of inlay and onlay ceramics was performed according to the following procedures. The zirconia-based specimens were etched for 180 seconds with Metal/Zirconia Primer (Ivoclar Vivadent AG). Hydrofluoric acid, 4.5% (IPS ceramic etching gel, Ivoclar Vivadent AG) was applied to the IPS e.max Press (Ivoclar Vivadent AG) surfaces for 60 seconds, rinsed thoroughly for 60 seconds, and air dried for 10 seconds. The interior surfaces of all specimens were silanized with porcelain primer (Monobond S, Ivoclar Vivadent AG) for 60 seconds and gently air dried. A bonding agent (Heliobond, Ivoclar Vivadent AG) was applied and left unpolymerized (polymerized after inlay placement).

Dual-polymerizing resin cement (Variolink II Base, Ivoclar Vivadent AG) was mixed with its catalyst (Variolink II high viscosity, Ivoclar Vivadent AG) in equal parts for 15 seconds, applied to the ceramic surface, cemented, and light polymerized. The ceramic specimen was cemented perpendicular to the pretreated surface using finger pressure, and excess material was removed with an explorer. The specimens were light polymerized with a minimum light intensity of 650 mW/cm^2 (Elipar Freelight 2, 3M ESPE AG) from the facial and occlusal directions for 20 seconds in each direction. The cement margin was finished using flexible polishing discs (Sof-Lex XT Pop-On, 3M ESPE AG). The specimens were exposed to thermal cycling at temperatures of 5°C and 55°C for a total of 5000 cycles. The dwell time at each temperature was 30 seconds, and the transfer time from one bath to the other was 2 seconds.

The teeth were subjected to axial compressive loading using a metal sphere of 6-mm diameter 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, Istanbul, Turkey). In order to reduce the local force peaks, 0.5-mm thick tin foil (Baoji Taihe Nonferrous Metal Co, Ltd, Shaanxi, China) was inserted between the metal sphere and the occlusal surface of the restoration. The force (N) required to fracture the restoration and the mode of fracture were recorded. The mode of fracture for each specimen was classified according to Burke[24] as follows:

- mode I: isolated fracture of the restoration;
- mode II: restoration fracture involving a small tooth portion;

Table 1: *Mean Fracture Resistance Values (SDs) and Statistical Categories of All Experimental Groups (n=10)*

Group	Code	Failure Load Mean (N)*
1	IT	2905.3 (398.8)[a]
2	I-e.max	2646.7 (360.4)[a]
3	I-Zirkon	2849.0 (328.0)[a]
4	O-e.max	1673.6 (677.0)[b]
5	O-Zirkon	2796.3 (337.3)[ac]

** Groups with different superscript letters are statistically significantly different according to the Tukey HSD test (p<0.05).*

- mode III: fracture involving more than half of the tooth, without periodontal involvement; and
- mode IV: fracture with periodontal involvement.

The results were analyzed by one-way analysis of variance (ANOVA) and Tukey HSD tests, and were considered statistically different at $\alpha = 0.05$.

RESULTS

The means and standard deviations for the fracture resistance of the test groups are shown in Table 1. The one-way ANOVA showed that there were statistically significant differences among the groups. The Tukey HSD test revealed that group 4 (1673.6 ± 677 N) showed significantly lower fracture strength values than the other groups. No significant differences were observed between the fracture strength values of the inlay groups (group 2 [2646.7 ± 360.4 N] and group 3 [2849 ± 328 N]) and the control group (group 1 [2905.3 ± 398.8 N]) (p=0.264). However, there were statistically significant differences between the fracture strength values of the onlay groups (groups 4 and 5) (p=.000). The O-Zirkon samples showed higher fracture strength values than those of O-e.max. There were significant differences between the I-e.max and O-e.max groups (p=.001); however, there were no significant differences between the I-Zircon and O-Zircon groups (p=.727). The mode of fracture for each group is shown in Table 2.

DISCUSSION

In this study, standardized inlay and onlay preparations were made for each molar tooth, and the restorations were adhesively cemented. The effects of cavity design and ceramic type (zirconia and lithium-disilicate–based ceramics) on the fracture resistance of restored teeth were evaluated.

Table 2: *Mode of Fracture of Restored Specimens According to Burke[24]*

Mode of Failure[a]	I-e.max	O-e.max	I-Zirkon	O-Zirkon
I	5	1	1	—
II	5	6	3	—
III	—	3	5	6
IV	—	—	1	4

[a] 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.

The results of this study revealed that there were no significant differences between the fracture strength values of the inlay groups; however, there were significant differences between the fracture strength values of the onlay groups. When the I-Zirkon and O-Zirkon groups were evaluated, the preparation type (inlay vs onlay preparation) did not affect the fracture strength values when compared with those of the control group. However, in the groups restored using IPS e.max Press, the O-e.max group (group 4) demonstrated significantly lower fracture strength values. Therefore, the null hypotheses that neither the preparation type nor the type of restoration material affects the fracture resistance of a tooth-restoration complex were partially rejected.

In the present study, the unprepared molars achieved the highest mean fracture strength values of 2905.3 ± 398.8 N. This value correlates with findings of a study conducted by Soares and others,[1] in which an average fracture strength value of 3143.1 ± 635.5 N was achieved in mandibular molars. However, the fracture strength values of the inlay and onlay groups in this study, except for the O-e.max group, were higher than the results of their investigation using feldspathic ceramic material for partial ceramic restorations in lower molars.[1] In the present study, the similarities between the fracture strength values of the inlay groups and the control group might be explained by the minimal reduction of the dental structure for an inlay preparation. The stabilization of a prepared tooth by placing a ceramic inlay using adhesive technique is considered to be a proven procedure in numerous *in vitro* studies[31,32] and explains the high fracture strength values. Although the mean fracture strength of the O-e.max group was significantly lower than the other groups, the mean fracture strength value of the O-Zirkon group was as high as that of the control group. This results from the mechanical structure of yttrium-stabilized zirconia, which is a glass-free, high-strength polycrystalline ceramic material with a flexural strength greater than 1000 MPa and fracture toughness of 9 to 10 $MPa \cdot m^{1/2}$.[17-19] It seems that the high strength of zirconia material may have compensated for the strength loss of the tooth resulting from the onlay cavity preparation. The lithium-disilicate–based onlay restoration-tooth complex did not withstand compressive loads as high as the zirconia-based onlays.

There are conflicting results in the literature regarding the fracture resistances of teeth restored with inlay and onlay ceramics. The results of O-e.max in the present study contrasted with those reported by Yamanel and others[33] who stated that the onlay design is more effective in protecting tooth structures than the inlay design. Conversely, Morimoto and others[26] reported that the fracture strength of teeth restored with inlay and overlay feldspathic ceramics with cusp coverage was similar to that of intact teeth. Soares and others[1] stated that the fracture resistance values of posterior inlay and onlay leucite-reinforced ceramic restorations were significantly higher than those of intact teeth. Habekost and others[14] investigated the fracture resistance of premolars restored with partial ceramic restorations using two different brands of feldspathic porcelain. Their results indicated that the inlays generated a significantly higher fracture resistance than onlay designs, but lower than that of intact teeth. Stappert and others[22] investigated all-ceramic partial coverage restorations for molars made of IPS e.max Press and demonstrated that their fracture resistance was comparable to that of natural unprepared teeth. In their more recent study, Stappert and others[15] investigated the masticatory fatigue loading and fracture resistance of different all-ceramic partial coverage restorations on natural molars. They found that fracture resistance values for maxillary molars restored with ProCAD/Cerec 3 were similar to those of intact teeth, but were significantly higher than those of IPS Empress and IPS e.max Press. The results of this study are consistent with Stappert and others[15] since the mandibular molars restored with ICE Zirkon onlays had higher fracture strength values than those of teeth restored with IPS e.max Press. However, the results of the present study conflict with those of Cubas and others,[34] who found that the fracture strength values of onlays with In-Ceram cores did not differ from those of feldspathic onlays with a total onlay preparation.

In addition to fracture resistance, it is also important to analyze the fracture modes. In this study, fractures in the I-e.max and O-e.max groups were observed in the restoration itself or in the restoration involving a small tooth portion. Soares and others[13] reported similar results using feldspathic ceramic in extensive inlays, and Burke[24] also affirmed that ceramic fractures before the natural tooth. In the I-Zirkon and O-Zirkon groups, fracture was observed in both the restoration and in the tooth. More severe fractures occurred in both the restoration and the tooth in the ICE Zirkon groups when compared with the IPS e.max Press groups. However, the more severe fractures that were observed in the ICE Zircon groups were in excess of what may ever happen in the oral environment.

Cavity preparation should be based primarily on the preservation of dental structure and on physical properties of the restorative materials. Khera and others[38] studied the effect of preparation depth, isthmus width, and interaxial dentin thickness on the potential for tooth fracture. They concluded that the depth of the preparation was the most critical factor in tooth fracture, whereas the width of the isthmus alone was the least critical. In the current study, ceramic inlays reinforced the dental structure of teeth that were prepared with one half of the intercuspal width, obtaining stiffness values that were similar to those of intact teeth. The lowest fracture strength values were recorded in the lithium-disilicate glass-ceramic onlay groups. Using this restorative material, preparations resulting in a greater loss of tooth structure appear to decrease the fracture resistance of the tooth-restoration complex. In zirconia-based ceramic groups, there were no significant differences in fracture strength values between different cavity preparation designs. With respect to limitations of this study, it was observed that fracture resistances of partial coverage restorations are material-dependent.

Restorations can fracture because of crack formation and propagation, which is especially true for ceramic restorations.[25] As preparations increase in size, the remaining tooth structure weakens, and occlusal loads induce greater cusp deflection. Some researchers have suggested that optimal restorations in teeth with large Class II MOD preparations are onlays that include cuspal coverage to reduce cuspal flexion under load.[26] Debate remains regarding the point at which onlays should be recommended instead of bonded inlays.[25]

It is difficult to determine which restorative material would be ideal for the restoration of posterior teeth.[40] In the past decades, indirect metal or amalgam restorations were the first choice for the restoration of partially destroyed teeth.[34,41] Magne and others[8] evaluated the fatigue strength of compromised molars restored using CAD/CAM composite resin inlays/onlays with and without fiber-reinforced immediate dentin sealing. They concluded that onlays (with or without fibers) increased the fatigue resistance of compromised molars. Dalpino and others[42] examined the fracture resistance of teeth restored with direct and indirect composite resin and indirect ceramic restorations. They found that bonded indirect ceramic restorations fractured at higher loads than direct and indirect composite resin restorations. A bonded indirect restoration using ceramic is the ideal option for restoration of teeth weakened by wide cavity preparation.[43] The advantage of posterior composites is that they can be placed in one appointment, while ceramic inlays usually require two appointments because of the time required for fabrication in the laboratory.

Resin cement used in adhesive restorations is elastic and tends to deform under stress, resulting in a higher resistance to fracture. Therefore, success of ceramic inlays is absolutely dependent on the creation of an uncompromised adhesive-tooth-ceramic interface.[44] Moreover, the elastic modulus of the luting agent may also affect the fracture strength values of the teeth restored with ceramic inlays and onlays. Cubas and others[34] found that luting agents with higher elastic modulus increased the fracture strength values of partial ceramic restorations.

This study also has some limitations. The continuous vertical load applied to the teeth in this study is not typical of clinical loading.[36] In terms of *in vivo* loading, the masticatory cycle consists of a combination of vertical and lateral forces, subjecting the ceramic to a variety of off-axis loading forces.[37] Cyclic loading may more accurately reproduce fatigue failures observed clinically. Other *in vitro* tests, such as stress distribution analysis, tension tests, and clinical studies need to be conducted to determine fracture strengths of various ceramic restorations with and without cuspal coverage.

CONCLUSIONS

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

1) Cuspal coverage decreased the fracture resistance of the posterior tooth and lithium-disilicate glass-ceramic restoration complex.
2) Teeth restored with zirconia ceramic inlays or onlays demonstrated fracture resistance similar to that of intact teeth.
3) The fracture modes in lithium-disilicate glass-ceramic samples were generally restricted to the restoration itself. Conversely, the fracture modes of zirconia samples generally involved both the restoration and the tooth.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service and/or company that is presented in this article.

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