

Fracture Resistance and Microleakage of Endocrowns Utilizing Three CAD-CAM Blocks

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Clinical Relevance

Fracture resistance and mode of failure of CAD/CAM-fabricated monoblock endocrowns varies widely between materials. Clinicians should be cautious with material selection for endocrown restorations.

SUMMARY

This study assessed marginal leakage and fracture resistance of computer-aided design/computer-aided manufacturing (CAD/CAM) fabricated ceramic crowns with intracoronal extensions into the pulp chambers of endodontically treated teeth (endocrowns) using either feldspathic porcelain (CEREC Blocks [CB], Sirona Dental Systems GmbH, Bensheim, Germany), lithium disilicate (e.max [EX], Ivoclar Vivadent, Schaan, Liechtenstein), or resin

nanoceramic (Lava Ultimate [LU], 3M ESPE, St Paul, MN, USA). Thirty extracted human permanent maxillary molars were endodontically treated. Standardized preparations were done with 2-mm intracoronal extensions of the endocrowns into the pulp chamber. Teeth were divided into three groups (n=10); each group was restored with standardized CAD/CAM fabricated endocrowns using one of the three tested materials. After cementation with resin cement, specimens were stored in distilled water at 37°C for one week, subjected to thermocycling, and immersed in a 5% methylene-blue dye solution for 24 hours. A compressive load was applied at 35 degrees to long axis of the teeth using a universal testing machine until failure. Failure load was recorded, and specimens were examined under a stereomicroscope for modes of failure and microleakage. Results were analyzed using one-way analysis of variance and Bonferroni *post hoc* multiple comparison tests ($\alpha=0.05$). LU showed significantly ($p<0.05$) higher fracture resistance and more favorable fracture mode (ie, fracture of the endocrown without fracture of tooth) as well as higher dye penetration than CB and EX. In conclusion, although using resin

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nanoceramic blocks for fabrication of endocrowns may result in better fracture resistance and a more favorable fracture mode than other investigated ceramic blocks, more microleakage may be expected with this material.

INTRODUCTION

Restoration of endodontically treated teeth continues to be a challenge in reconstructive dentistry. A common protocol of restoring such teeth has been to build up the tooth with a post and core to aid the retention of an overlying crown. This can be achieved through a direct approach using a prefabricated intraradicular post followed by a direct core material or through an indirect post and core restoration for teeth with more extensive loss of tooth structure. However, many clinical and laboratory studies have reported that placing a post will contribute to the retention of the core portion of the restoration but may have a weakening effect on the root.¹⁻⁵ The use of intraradicular post and cores is complicated by the necessity to prepare an adequate ferrule, which reduces the risk of failure through root fracture.⁶ Failure of post and core systems may be due to different mechanical behaviors relative to tooth structure in response to intraoral cyclic stresses.⁷ This failure can be classified as repairable failure (favorable fracture) or nonrepairable failure (catastrophic fracture) that requires extraction of the tooth and subsequent prosthetic replacement.^{8,9}

With the increasing popularity of adhesive dentistry, a shift in treatment decisions toward more conservative modalities has been observed, and the need for conventional post and cores has become less clear.¹⁰ Ceramic inlays, onlays, and endocrowns have been introduced as alternative restorations for endodontically treated molars, depending on the availability of remaining tooth structure.¹¹⁻¹⁴ Initially proposed by Pissis¹⁵ in 1995, endocrowns are a type of restoration consisting of the entire core and crown as a single unit (ie, monoblock). Endocrowns use the available surface of the pulp chamber axial walls as macroretentive resources and adhesive resin cement as a means of micromechanical retention.¹⁶ Additionally, this type of restoration is made available through computer-aided design/computer-aided manufacturing (CAD/CAM) technology, which provides the possibility for chair-side design and fabrication.

Endocrowns are especially indicated in cases of inadequate clinical crown length, insufficient interocclusal space, and extensive loss of dental tissues that do not allow the use of an adequate ferrule.¹⁷

Moreover, endocrowns have the advantage of preserving tooth structure, reducing the need for auxiliary macroretentive features, and saving patient's and operator's time due to fewer clinical steps and absence of the laboratory procedures needed for fabricating conventional crowns. This approach has shown promising results and comparable short-term survival when compared to post, core, and crown systems.¹⁸⁻²²

A wide collection of ceramic materials has been available for CAD/CAM technology, ranging from relatively weak feldspathic ceramic and leucite glass ceramic to high-strength lithium disilicate glass ceramic and zirconium oxide.²³ Most recently, a resin nanoceramic has been introduced for permanent CAD/CAM fabricated restorations.^{24,25} Ultrastructure, physical, and mechanical properties of available CAD/CAM materials vary widely, and, accordingly, their mechanical behavior in the tooth-restoration complex is expected to vary as well.^{26,27}

With the intent of increasing the amount of information about the biomechanical behavior of these materials when used for endocrowns, the present study evaluated the microleakage, fracture resistance, and failure modes of three types of CAD/CAM fabricated restorations when they were submitted to an oblique compressive force.

METHODS AND MATERIALS

Tooth Collection and Preparation

Thirty freshly extracted human permanent maxillary first and second molars with approximately similar mesiodistal/buccolingual dimensions and root length were collected after patients' informed consents were obtained under a protocol approved by the institutional review board and in conformity with the university's guidelines for handling biological tissues. Teeth were ultrasonically cleansed of calculus and soft tissues, stored in a 1% chloramine-T solution at 4°C, and used within one month. Teeth were sectioned parallel to the occlusal surface at 2 mm above the cemento-enamel junction (CEJ) to remove occlusal tooth structure and to deroof the pulp chamber.

Endodontic Procedures

Removal of pulp tissues was done with an endodontic reamer, and determination of root canal lengths was done radiographically with endodontic files inserted in the canals. Standardized canal enlargement was performed with an engine-driven rotary NiTi system (ProTaper, Dentsply Maillefer, Ballaigues, Switzerland).

Table 1: *The Materials Tested in This Study*

Code	Material	Manufacturer	Batch Number	Ceramic Type	Fracture Toughness (MPa m ^{1/2}) ^a	Modulus of Elasticity (GPa) ^a
CB	CEREC Blocks	Sirona Dental Systems	108290	Aluminosilicate (feldspathic) ceramic	1.4 (0.2)	45.0 (0.5)
EX	e.max CAD	Ivoclar Vivadent	P84622	Lithium disilicate glass ceramic	2.6 (0.3)	81.0 (3.3)
LU	LAVA Ultimate	3M ESPE	N333039	Resin nanoceramic	2.0 (0.2)	12.8 (1.0)

^a Values obtained from manufacturer's data.

land) using a crown-down technique; 1% NaOCl was used as an irrigant for 10 seconds between each file. Root canals were obturated with a thermoplasticized gutta-percha (Calamus Dual, Dentsply Maillefer, Woodinville, WA, USA) and root canal sealer (AH 26 sealer, Dentsply Maillefer) according to the manufacturer's instructions, providing a standardized filling procedure.

The superior aspect of the gutta-percha material was removed using a small carbide bur to 1 mm below the orifice of each canal, then flowable resin composite (Filtek Z350XT flowable, 3M ESPE, St Paul, MN, USA) was used to fill the canals up to the level of the pulp chamber.

Endocrown Preparation

The teeth were individually fixed in fast-cure acrylic resin (Fastray, Harry J. Bosworth Co, Skokie, IL, USA) using polyvinyl chloride rectangular molds. The roots were embedded in resin up to 2 mm below the CEJ (simulated bone level). Intracoronal height of the prepared walls was reduced to 2.0 mm, measured from the internal cavity margin to the floor of the pulp chamber, using a periodontal graded probe.

A standardized cavity preparation was performed in all teeth limited to removal of undercut areas of the pulp chamber and alignment of its axial walls with an internal taper of 8-10 degrees using a tapered diamond coated stainless-steel bur with a rounded end (G845KR, Edenta, Basel, Switzerland) held perpendicular to the pulpal floor. All internal line angles were rounded and smoothed using the same type of bur. The axial walls were prepared from the pulpal side to provide for a standardized cavity wall thickness of 2.0 ± 0.2 mm measured with a digital caliber (Mitutoyo IP 65, Kawasaki, Japan) having a precision of 0.001 mm.

Endocrown Fabrication and Thermocycling

CAD/CAM ceramic endocrowns were fabricated with a CEREC AC system by using the software package provided (CEREC 3D, version 3.8, Sirona Dental

Systems GmbH, Bensheim, Germany). All endocrowns were designed to have similar occlusal anatomy by using the biogeneric reference option as well as having the same occlusogingival height. Teeth were randomly distributed into three equal groups (n=10) according to the block material: feldspathic block ceramic (CB), lithium-disilicate blocks (EX) and resin nanoceramic blocks (LU). Tested materials are listed in Table 1.

Before cementation, the marginal adaptation of the endocrowns was checked using a Measurescope (UM-2, Nikon, Tokyo, Japan), and any specimen with a marginal gap >40 microns was rejected and replaced with a new specimen. Intaglio surfaces of each endocrown were treated according to the manufacturer's instructions for the respective block material. Etching with 5% hydrofluoric acid gel (IPS Ceramic Etching Gel, Ivoclar Vivadent, Schaan, Liechtenstein) was done for 60 seconds for CB or 20 seconds for EX, then rinsed for 60 seconds with running water and dried for 30 seconds with oil-free, moisture-free air. Intaglio surfaces of LU crowns were sandblasted with ≤25-µm aluminum oxide particles (MicroEtcher CD, Danville Materials, San Ramon, CA, USA), then sand was removed with alcohol and dried with oil-free, moisture-free air. A ceramic primer containing silane coupling agent (Monobond Plus, Ivoclar Vivadent) was applied to the intaglio surfaces of all endocrowns and allowed to dry for 60 seconds.

Prepared tooth surfaces were etched with 37% phosphoric acid-etching gel for 15 seconds, rinsed for 20 seconds, and dried with oil-free air for another 5 seconds. Dentin primer (Syntac, Ivoclar Vivadent) was applied for 15 seconds and dried thoroughly for 10 seconds, then dentin adhesive (Syntac, Ivoclar Vivadent) was applied for 10 seconds and dried thoroughly for another 10 seconds. Adhesive resin (Heliobond, Ivoclar Vivadent) was applied and air blown to a thin layer for 15 seconds. All specimens were cemented with dual cure resin cement (Variolink II, Ivoclar Vivadent) under a constant load of 50 g for 30 seconds. Excess material was removed

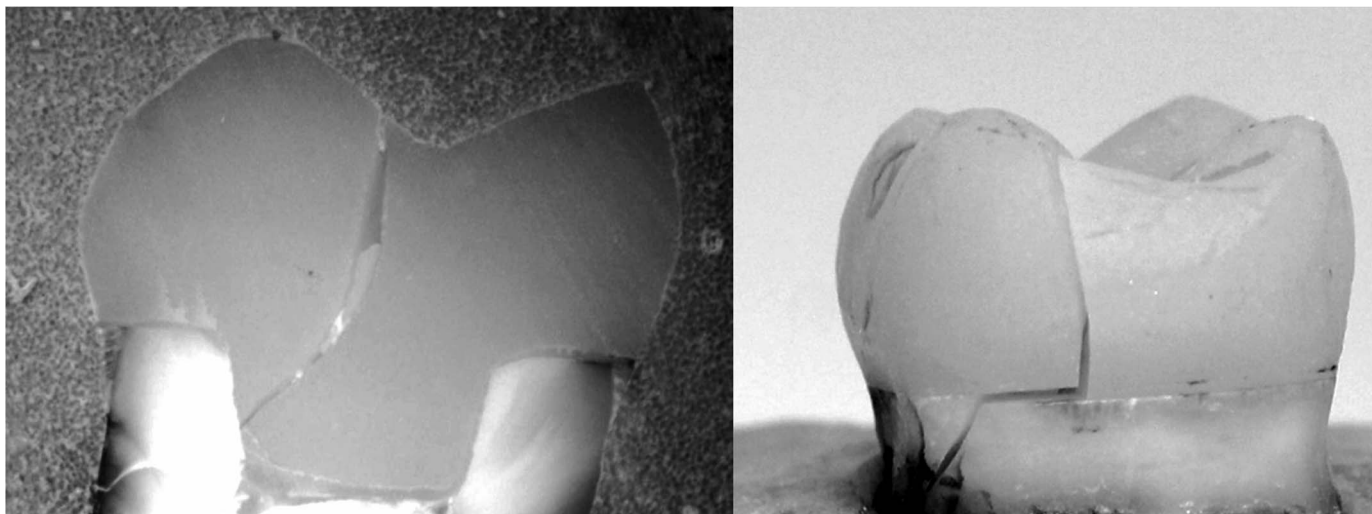


Figure 1. Crack of endocrown/tooth complex above margin of bone level simulation (type III, acceptable failure) characteristic for feldspathic ceramic crowns (CB) with little penetration of the dye materials at the margin.

with the help of a microbrush. Restoration margins were covered with a glycerine gel (Liquid Strip, Ivoclar Vivadent) to prevent oxygen inhibition of polymerization. The resin cement was light activated at each surface for 20 seconds using a light-emitting diode curing unit (Demetron A.1, Kerr/Sybron, Orange, CA, USA) with a 12-mm-diameter curing-light tip in standard mode with irradiance output of $1000 \pm 50 \text{ mW/cm}^2$ held at a surface-tip distance of 0.5 mm. Output intensity was monitored after every fifth specimen using a handheld radiometer (Kerr/Model 100, Demetron Research, Orange, CA, USA). Margins of the restorations were finished with sandpaper polishing discs (Sof-Lex, 3M ESPE).

Specimens were stored in double-distilled water at 37°C for one week to allow for bonded interface maturation. Specimens were subjected to 5000 thermal cycles between two water baths of 5°C and 55°C with a dwell time of 30 seconds at each temperature (Thermocycler, Willytec, Munich, Germany). After thermocycling, the entire surface of each specimen was covered with two coats of varnish up to 1 mm from the crown margins. Teeth were soaked in an aqueous solution of 5% methylene blue dye for 24 hours at 37°C . Following dye exposure, the teeth were rinsed thoroughly with a water syringe for 30 seconds.

Fracture Resistance Testing

Each mounted tooth was placed in a two-dimensional precision vice (FT-USV80, Firstec Inc, Osaka, Japan), positioned at an angle of 35 degrees between the long axis of the tooth and the loading jig in a universal testing machine (Sintech Renew 1123, TestWorks

4.08, MTS, Eden Prairie, MN, USA) with a 2.5-kg load cell. Force was applied through a stainless-steel ball (2.5 mm in diameter) representing the antagonist tooth. Load was applied to the incline of the palatal cusp at a crosshead speed of 0.5 mm/min. The fracture load needed to cause failure of the specimen, which was signaled as a peak in the load-displacement tracing, was recorded in newtons (N). Mode of fracture was examined for each specimen and categorized according to the following descriptions:

- Type I: complete or partial debonding of the endocrown without fracture (favorable failure)
- Type II: fracture of the endocrown without fracture of the tooth (favorable failure)
- Type III: fracture of the endocrown/tooth complex above the height of bone level simulation (acceptable failure)
- Type IV: fracture of the endocrown/tooth complex below the height of bone level simulation (catastrophic failure)

Microleakage Testing

The fractured coronal portion of the specimens were reassembled and embedded in fast-cure resin (Fastray, Harry J. Bosworth Co). Resin blocks were allowed to polymerize for 24 hours. Each specimen was sectioned buccolingually with a slow-speed diamond precision saw (Isomet 1000, Buehler, Lake Bluff, IL, USA) under water cooling, producing five sections from each tooth. The two outermost sections were discarded, and the middle three tooth sections were used for dye penetration evaluation.

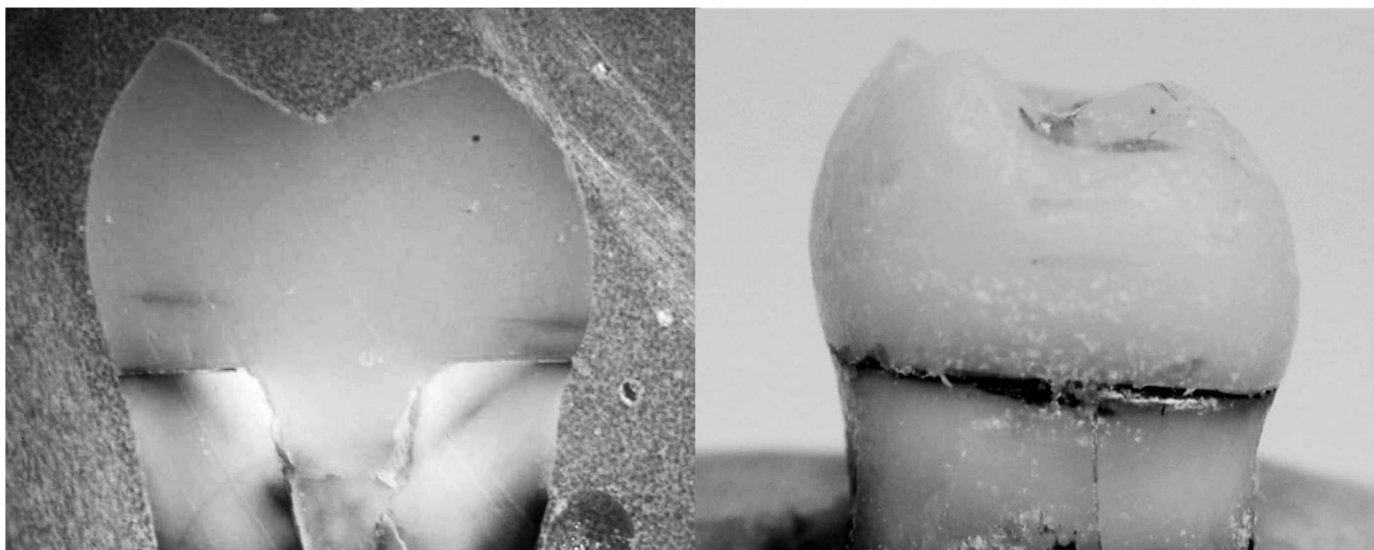


Figure 2. Crack of endocrown/tooth complex below margin of bone level simulation (type IV, catastrophic failure) characteristic for lithium disilicate (EX) crowns with little penetration of the dye materials at the margin.

A digital multi-axis dimensional measurement device (Quadra-Chek 200, Metronics Inc, Bedford, NH, USA) connected to a Measurescope (UM-2, Nikon) was used to measure the depth of dye penetration with the help of a built-in digital camera (Digital Microscope Camera, Model DMC 1, Polaroid, PLR Ecommerce, LLC, Minneapolis, MN, USA) and fiber-optic light at a magnification of 90×. Dye penetration at the tooth/luting agent interface at both the buccal and the lingual margins of each section was measured in millimeters, and dye penetration for each tooth was calculated from the average of all the readings of the three sections (Figures 1 through 3).

Statistical Analysis

Results were analyzed with statistical software (SPSS version 20.0, SPSS Inc, Chicago IL, USA) using a one-way analysis of variance (ANOVA) and

Bonferroni *post hoc* multiple comparison tests ($\alpha=0.05$).

RESULTS

The means, standard deviations, and 95% confidence interval levels for both fracture resistance and dye penetration for the three investigated CAD-CAM blocks are presented in Table 2. ANOVA revealed that there was a statistically significant difference between the groups ($p<0.05$) for both fracture resistance and dye penetration. The Bonferroni test (Table 3) indicated that there was a significantly higher ($p<0.05$) mean fracture resistance value for LU (1583.28 ± 170.55 N) when compared to both CB and EX (1340.92 ± 97.80 and 1368.76 ± 237.34 N, respectively). There was no significant difference between mean fracture resistance of EX and CB. Additionally, the mean dye penetration values of LU (2.80 ± 0.19 mm) were found to be significantly higher ($p<0.05$) than those of CB and EX ($1.111 \pm$

	Material	Mean	Standard Deviation	95% Confidence Interval for Mean		Minimum	Maximum
				Lower Bound	Upper Bound		
Dye penetration (mm)	CB	1.11	0.19	0.98	1.24	0.92	1.37
	EX	1.91	0.14	1.81	2.01	1.70	2.06
	LU	2.80	0.18	2.67	2.93	2.51	2.94
Fracture resistance (N)	CB	1340.92	97.80	1270.96	1410.88	1240.05	1494.48
	EX	1368.77	237.34	1198.99	1538.55	811.36	1746.28
	LU	1583.28	170.55	1461.27	1705.28	1316.89	1746.28

Table 3: Results of Bonferroni Post Hoc Test From Multiple Comparison of Dye Penetration and Fracture Resistance of Different CAD/CAM Blocks

Dependent Variable	(I) Block Type	(J) Block Type	Mean Difference (I – J)	Standard Error	Significance
Dye penetration	CB	LU	-1.690*	0.076	0.000
		EX	-0.802*	0.076	0.000
	EX	CB	0.802*	0.076	0.000
		LU	-0.888*	0.076	0.000
	LU	CB	1.690*	0.076	0.000
		EX	0.888*	0.076	0.000
Fracture resistance	CB	LU	-242.358*	79.574	0.015
		EX	-27.848	79.574	1.000
	EX	CB	27.848	79.574	1.000
		LU	-214.510*	79.574	0.036
	LU	CB	242.358*	79.574	0.015
		EX	214.510*	79.574	0.036

* The mean difference is significant at the 0.05 level.

0.185 and 1.91 ± 0.14 mm, respectively), which were also found to be significantly different.

Modes of failure of the three tested CAD/CAM blocks are presented in Table 4. The results showed that 50% of the CB specimens exhibited acceptable fracture type (Figure 1) and 30% catastrophic fracture. High prevalence of catastrophic fracture (70% type IV) was demonstrated by EX, as shown in Figure 2. Meanwhile, LU exhibited a higher occurrence of favorable fracture modes (20% type I and 60% type II), as demonstrated in Figure 3.

DISCUSSION

This *in vitro* study simulates the compromised situation of extensive loss of tooth structure, which does not readily allow for the use of the ferrule effect in crown preparation. Under such circumstances, endocrowns take advantage of recent developments in adhesives, ceramics, and CAD/CAM technologies in an approach that is based mainly on a decay-oriented design concept.²⁸ This concept is built on a minimally invasive preparation that preserves maximum amounts of tooth surface for bonding and where extensive macroretention designs are no

longer a prerequisite. The utilization of the available space inside the pulp chamber adds to the stability and retention of the restoration and reduces the operational errors possible during post-space preparation.²⁰ It has been assumed that through establishing adhesion, the occlusal stresses that occur during function are transmitted to the walls of the pulp chamber. The deeper the pulp cavity and resulting intracoronal extension, the greater the surface area that can be utilized for adhesive retention and transmission of masticatory forces.¹⁶

In an attempt to exclude the effect of variances in the intracoronal extensions of the endocrowns, a standardized cavity design following guidelines by Pissis¹⁵ was used. The preparations were done to allow for an intracoronal extension of 2 mm. This minimal extension allowed for testing endocrown/tooth systems with minimal remaining tooth structure, in other words, the ability of the remaining tooth structure to retain the restoration and the ability of the adhesive restoration to reinforce the remaining weakened tooth structure. A previous study had reported clinical evaluation of endocrowns with intracoronal extensions varying from 1 to 4 mm, corresponding to variances in pulp chamber depth.¹⁷ Yet no studies report the effect of the dimension of the intracoronal extension on fracture resistance and modes of failure. One study reported that the possible failure of the endocrown was associated with the height of the endocrown itself (position of the finish line) and the height level of the applied force on the crown (contact with opposing teeth) rather than the concept of the endocrown itself.²⁹ Therefore, in the present study, variability in endocrown dimensions was controlled using the

Table 4: Modes of Failure (%) of Feldspathic Porcelain (CB), Lithium Disilicate (EX), and Resin Nanoceramic (LU)

Material	Mode of Failure %			
	Type I	Type II	Type III	Type IV
CB	10	10	50	30
EX	0	0	30	70
LU	20	60	20	0

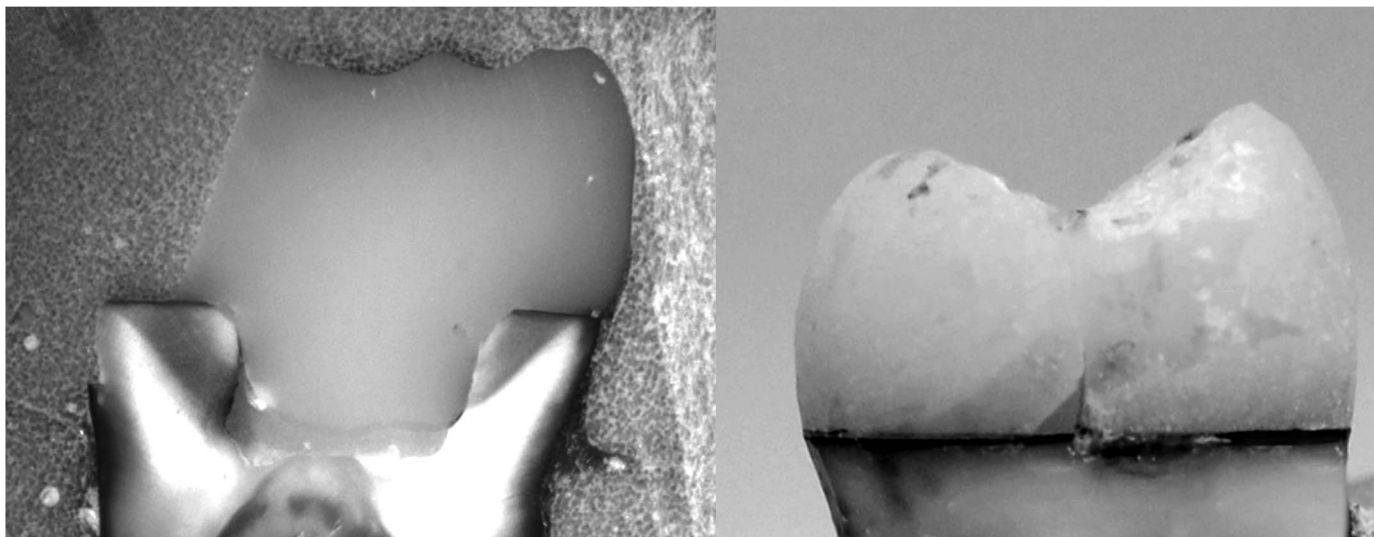


Figure 3. Crack of endocrown without fracture of tooth (type II, favorable failure) characteristic for nanocomposite (LU) crowns with deep penetration of the dye material.

Cerec technology, which allowed the fabrication of standardized restoration size, shape, and cuspal inclines and hence standardizing the point of load application during testing.

In complex multilayered restorations, such as cemented ceramic restorations, several factors contribute to the mechanical behavior of the restoration/tooth system. The intrinsic strength of each component of the system (ie, tooth, adhesive system, luting cement layer, and restoration), the thickness of the restorative material, the ratios of elastic moduli between the restoration material, the luting cement and dentin, and finally the quality of the adhesive interface between these layers in terms of bond strength and presence of micro- or nanoleakage are all factors that play a role in the behavior of such restorations.³¹ Results of the present study showed a significantly higher mean fracture resistance value for LU when compared to EX and CB. These results were in agreement with another study by Heo and others,³⁰ who reported significantly higher impact fracture resistance and fewer cases of complete fracture of LU when compared to lithium disilicate.

The unique composition of LU allows the material to have a modulus of elasticity (12.8 GPa) similar to that of dentin (5.5-19.3 GPa).³² The modulus of elasticity influences the susceptibility to fracture of a cemented ceramic restoration since materials with more compatible elastic moduli tend to bend under load and distribute stresses more evenly, while rigid materials with different elastic moduli, such as lithium disilicate, produce stress concentrations at

critical areas that might cause catastrophic failures.^{33,34} Failure modes reported in this study support such an explanation, as none of the LU specimens showed catastrophic failure modes, while 80% had favorable modes of failure. On the other hand, 70% of the EX specimens had catastrophic failure modes.

Moreover, weak bond strength between restorations and resin cements could lead to a nonhomogeneous distribution of forces that could result in cohesive failure of the resin cement. Multiple authors have evaluated the bond strength of feldspathic and lithium disilicate-based glass ceramic to composite resin or resin cements using tensile, microtensile, shear, and microshear mechanical tests^{23,35-37} and concluded that lithium-disilicate glass ceramic exhibits significantly higher bond strengths than feldspathic ceramics independent of surface conditioning, which is attributed mainly to its unique crystalline microstructure. Another study reported higher bond strength to resin cement and more favorable modes of failure of LU when compared to feldspathic porcelain monoblocks.³⁸ These findings can provide understanding for the results of the current study, as the bond strength of LU to composite resin is expected to be better than that found with ceramics.^{39,40} The presence of resin matrix in LU blocks should facilitate bonding to resin composite luting materials, resulting in more uniform stress distribution when compared to feldspathic and reinforced ceramics and therefore better fracture resistance. It is worth mentioning that although the application of a single monotonic load

to cause failure does not represent the clinical situation, in which repetitive cyclic fatigue loading is characteristic, the setting of this study provided a controlled environment that allows comparing the behavior of materials under the applied circumstances.

Thermocycling and application of mechanical loading are widely accepted methods when testing for *in vitro* microleakage and fracture resistance to simulate aging and stress at the adhesive interface.⁴¹ Exposure of the hybrid layer to hot water during thermocycling can affect the adhesive layer by accelerating the hydrolysis of unprotected collagen and extracting poorly polymerized resin. Additionally, stresses are generated at the adhesive interface during thermocycling due to the difference in the coefficient of thermal expansion between the restorative materials and the tooth structure. The linear coefficient of thermal expansion has been suggested as an important factor that influences microleakage.^{42,43} This factor is influenced by the composition of the restorative material. A greater difference in the linear coefficient of thermal expansion between tooth and restorative material leads to the generation of excessive stresses with temperature fluctuation that may result in microcracks that propagate along the bonded interface, causing a gap to form.

In the present study, LU showed a significantly higher dye penetration than CB and EX. Unlike the other ceramics, LU contains 80% nanoceramic particles embedded in a highly cured resin matrix (20%).³² It is thought that this unique composition results in a higher coefficient of thermal expansion in comparison to that of ceramic materials and dentin, which in sequence would exaggerate the effect of thermocycling on margin quality of this material and therefore could result in greater microleakage.⁴⁴

One limitation of this study was the use of one type of adhesive and luting cement system. The use of other systems may have resulted in different outcomes. Additionally, cyclic fatigue, bond strength data, and the effect of the endocrown intracoronal extension dimension on the fracture resistance and pattern of failure were not evaluated. Therefore, more studies are needed to investigate the effect of these variables on the mechanical behavior of endocrown restorations.

CONCLUSION

In comparison to feldspathic and lithium disilicate ceramics, the higher fracture resistance and more favorable failure of resin nanoceramic, may favor its

use for endocrown restoration of endodontically treated teeth with extensive loss of tooth structure. However, higher amounts of microleakage may jeopardize the long-term performance of this material.

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Note

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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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