FRACTURE RESISTANCE OF LITHIUM DISILICATE RESTORATIONS FOLLOWING ENDODONTIC ACCESS PREPARATION; AN *IN VITRO* STUDY

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2014

Major Subject: Oral Biology

ABSTRACT

The purpose of this in vitro study was to determine the effect of endodontic access preparation on the fracture resistance and microstructural integrity of monolithic pressed and monolithic milled lithium disilicate complete coverage restorations. Twenty monolithic milled (IPS e.max Press) and twenty monolithic milled (IPS e.max CAD) lithium disilicate restorations were fabricated and adhesively bonded to forty identical epoxy resin dies. Ten of the pressed and ten of the milled crowns were accessed for a simulated endodontic treatment and subsequently repaired using a porcelain repair system and composite resin. All specimens were cyclically loaded for 250,000 cycles (1.6Hz, 50-250N) and loaded to failure in a universal testing machine. Force data were recorded and analyzed using a statistical analysis software. An analysis of variance (ANOVA) followed by a post hoc test (Sidak's correction) was used to indicate significant differences between the groups ($p<0.05$). A Weibull analysis was also performed in order to calculate the Weibull parameters (modulus and characteristic failure load) for each group, and therefore compare their mechanical reliability. Eight (four pressed and four milled) additional restorations were also fabricated, in order to complete an SEM analysis and evaluate the surface damage created by the endodontic access preparation.

A statistically significant difference ($p=0.019$) was noted between the pressed intact and pressed repaired restorations, as well as between the pressed intact and milled repaired restorations ($p=0.002$). There was no statistically significant difference noted between the milled intact and milled repaired restorations. The milled repaired restorations had the lowest mean failure load, whereas the pressed intact restorations had the highest. Specimens that were examined under SEM showed edge chipping that involved primarily the glaze (IPS e.max Ceram) layer around the access openings.

Endodontic access preparation of lithium disilicate restorations resulted in a significant decrease in the fracture resistance of the pressed (IPS e.max Press) specimens, but not in the milled (IPS e.max CAD) restorations.

DEDICATION

This thesis is dedicated to my mentor Dr. William W. Nagy, Director of the Graduate Prosthodontics Program at Texas A&M University Baylor College of Dentistry, who trusted me and changed my life through giving me this wonderful opportunity to join the prosthodontic society.

It is also dedicated to my beloved family, my parents and my sister, who have been unwaveringly supporting me throughout my academic life for almost a decade.

ACKNOWLEDGEMENTS

Before anybody else, I would like to thank my Teacher, Dr. William W. Nagy. Dr. Nagy changed my life exactly four years ago, when he offered me a position at the Graduate Prosthodontic Program at Texas A&M University Baylor College of Dentistry. Excited as I was back then, I could hardly imagine the huge impact that this would have in my future, not only as a prosthodontist, but as a person as well. Under his wings and as one of his students I matured as a person and I learned to set goals for myself. I would be a different individual if I had never been given this amazing opportunity; and for this, I will always be grateful to him.

I would also like to thank my committee members; Dr. Elias Kontogiorgos, Dr. John T. Goodman and Dr. David F. Murchison. They all provided helpful comments and insights that definitely improved the overall quality of my thesis.

This research project would never be completed without the financial support from the American Academy of Fixed Prosthodontics, who awarded it with the Tylman Research Grant in June 2013 and eventually with the second place at the Stanley D. Tylman Research Competition 2014. This award was a great honor for everybody who participated in this study. In addition, I would like to thank the State Scholarship Foundation (SSF) from Greece as well as the Onassis Foundation for giving me the privilege to be one of their scholars during my residency (SSF; 2011-2013, Onassis Foundation; 2013-2014).

I also want to extend my gratitude to several people from Baylor College of Dentistry; Dr. Steve W. Karbowski, Head of the Restorative Sciences Department and Dr. Venu Varanasi, Assistant Professor of the Biomedical Sciences Department, who provided support and guidance during several steps of the project. In addition, I would like to thank John Wilson, currently a third year Dental student at Baylor College of Dentistry, who helped me during various steps of the project as well, and showed a great interest in the whole process. I also wish to thank Dr. Jason Griggs, Associate Dean of Research and Chair of the Department of Biomedical Materials Science at the University of Mississippi School of Dentistry, for his assistance in conducting the Weibull analysis after the data collection.

Thanks also go to my co-residents and friends, as well as all the faculty members at the Graduate Prosthodontics program at Baylor, who tolerated me for three years and created a very fun and stimulating working environment for me. And of course, I need to express my endless appreciation for my friends in Greece, some of them being next to me for over twenty years, who always stand by my side in everything I do and never cease being an amazing network of support, regardless the thousands of miles that may keep us apart.

And of course - last but not least, I am grateful to my family, my parents George and Stavroula and my sister Spyridoula, for their constant moral support and their unswerving belief in me that has made all the difference.

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1. INTRODUCTION AND LITERATURE REVIEW

It is common knowledge among restorative dentists that any tooth planned to receive a full coverage restoration should be tested for pulp vitality before proceeding with tooth preparation. Any pulp pathology that may be identified should be addressed before restorative treatment is even initiated. However, even if careful initial assessment does not lead to the diagnosis of pulpal disease, it has been reported that endodontic-related complications may arise after the placement of the final restoration. Goodacre et al. reviewed the clinical complications associated with single crowns and reported a mean incidence of 1% for the need of endodontic treatment after all-ceramic crown preparation, which can increase up to 11% if the tooth served as an FDP abutment [1]. Bergenholtz et al. studied the endodontic complications following prosthodontic treatment in patients with periodontal disease and reported an incidence of up to 15% for pulpal necrosis in teeth with initially vital pulps that underwent prosthodontic treatment [2]. In another study, Cheung reported that 4% of teeth receiving full-coverage restorations develop pulpal necrosis [3]. Goldman et al. stated that the clinical impression of many endodontists is that 20% to 50% of their procedures are performed through complete-coverage crowns [4].

It is apparent that attempting to perform endodontic treatment through a complete coverage restoration can be frustrating for both the endodontist and the restorative dentist. In those cases, endodontic treatment has to be rendered by preparing an access opening to the pulp through the crown. This imposes several challenges to the specialist attempting the endodontic treatment. First, there are no clinical anatomical landmarks to orientate the pulp chamber location. The overlying crown covers the remaining coronal tooth structure, and the endodontist must use his clinical judgment to design the appropriate access opening. Second, during access preparation for the endodontic treatment, a significant amount of the dentin core will have to be removed, resulting in a significantly weaker core once the endodontic treatment is completed; even worse, the amount of this remaining core cannot be visualized in order to determine whether it is adequate to support the crown or not . In addition, endodontic access preparation through all-ceramic crowns creates two additional specific concerns; first, ceramics are poor conductors of heat, therefore heat formation during endodontic access preparation is hard to control. Second, access and instrumentation with rotary instruments may induce microcrack formation which will cause the restoration to fail upon their propagation over time.

Several studies have attempted to provide useful information in order to create the appropriate treatment protocol for these cases. In 1962, Michanowicz et al. were the first to describe the procedure of gaining access to the pulp chamber through porcelain jacket crowns. Avoiding placement of the rubber-dam clamp on the crown, high speed diamond instrumentation and copious water irrigation, were the authors' primary suggestions [5]. Since then, proper bur selection has been emphasized in the literature, and most studies conclude that it is not the potential for fracture but rather the inability to easily penetrate the ceramic material that contraindicates the use of carbide burs during preparation of high-strength ceramics [6], [7], [8]. Air abrasion has also been proposed as a novel method of creating endodontic access preparations through all-ceramic crowns. This technique was associated with decreased damage to the crown, but was determined to be less effective when compared to diamond and carbide bur instrumentation [9]. In an attempt to establish a protocol for the treating endodontist, Davis [10] suggested using diamond burs along with copious water irrigation. He also suggested keeping the access preparation at least 2mm away from the restoration margin and having the bur at a 90-degree angle to the ceramic surface. It should also be kept in mind that the higher crystalline content of lithium disilicate crowns (70 vol%, instead of ~55 vol% of other glass-ceramic systems) [11] makes the penetration through those crowns more difficult. A recent study suggested using smaller-grit (126µm) diamonds during endodontic access preparation in lithium-disilicate crowns. The authors concluded that an efficient rotary instrument seems to cause less damage to the restoration, and also protects the integrity of the adhesive interphase [12].

However, even after the endodontic treatment is successfully completed, the clinical challenge remains for the restorative dentist, who will need to determine the appropriate definitive treatment protocol. There are basically two options; either to manage the access opening with a restorative material that will ideally bond to the existing crown and remaining core, or to replace the entire restoration. The decision requires clinical judgment, and it primarily relies on the extent of damage that occurred during the endodontic procedure. Even though there is a lack of literature providing evidence to support one treatment modality over the other, patients will most frequently opt for the first option, primarily due to financial limitations.

There are two crucial factors that need to be considered in the attempt to rationalize the repair of the ceramic surface with a composite material; these are the feasibility of a bond formation between those two different materials, as well as the effect of this repair to the mechanical properties of the restoration. Even though the repairing procedure for ceramics and its associated mechanisms have been adequately described in the literature [13-19], the fracture toughness of the repaired all-ceramic crown has not been adequately examined yet.

In general, the strength of dental ceramics is primarily influenced by internal flaws and their distribution throughout the microstructure of the material. It has been stated that microcracks act as stress-intensifiers, facilitating fracture initiation and ceramic failure [20]. Flaws can be introduced into the ceramic mass during the fabrication process or they can be inherent in the microstructure [21], [22]. It is also well documented that the moisture present in the oral environment acts as an aggravating factor, because it allows the slow growth of cracks. [16]. Preparation for an endodontic access opening through an all-ceramic crown imposes the danger of initiating additional microcracks within the internal structure of the material and therefore put the restoration in even greater risk for fracture.

Several studies attempt to identify the effect of endodontic access preparation on the internal structure of all-ceramic crowns. Teplitsky and Sutherland evaluated the effect of endodontic access opening on fifty-six alumina core crowns (Cerestore) fabricated on extracted teeth. Scanning electron microscope (SEM) analysis revealed cracking in only one crown; however, chips and roughness were evident on the external outline form of all access openings. The authors did not correlate the surface damage rate with the instrumentation employed for the access preparation; however, they concluded that diamond burs were more effective than carbide burs [7]. Sutherland et al. examined the effect of endodontic access preparation on forty-two Dicor crowns fabricated on extracted teeth. The access openings were made under water spraying, using either round diamonds or tapered fissure carbide burs. The incidence for crown fracture was 4.8% and the incidence for crazing was 16.7%. The authors also concluded that high-speed diamond instrumentation caused less damage than carbide burs [6].

The fracture resistance of all-ceramic crowns before and after endodontic access preparation and subsequent repair has been examined in two studies. Wood et al. examined the effect of endodontic access preparation on twenty-four alumina and twenty-four zirconia core all-ceramic crowns that were fabricated on epoxy resin dies. All access openings were repaired with a direct restoration, using a porcelain repair system. Environmental scanning electron microscope (ESEM) analysis revealed edge chipping around all access openings, in addition to cracking and chipping of the core and/or cement on some specimens. Endodontic access preparation resulted in a significant decrease in strength of zirconia specimens, but not in alumina specimens; however, load to failure for zirconia crowns was twice as much as the load to fracture for alumina crowns [23].

Qeblawi et al. evaluated the effect of simulated endodontic access preparation on the failure load of sixty lithium disilicate crowns (IPS e.max) that were fabricated on composite resin dies. The access openings were made using round and round-end tapered diamond rotary instruments of three different grit sizes. All crowns were repaired with a direct composite resin restoration. The authors found that larger-grit diamonds had a negative effect on the failure load of the repaired restorations and also that adhesively bonded restorations showed increased failure loads compared to conventionally cemented restorations [12]. This is the only study found that evaluates the effect of endodontic access preparation and subsequent repair on the fracture resistance of lithium disilicate crowns. However, a significant limitation of this study was that the specimens were not cyclically loaded prior to testing. It has been well documented that thermo-mechanical fatigue loading, also referred as "artificial aging" [24], in a simulated oral environment significantly affects the fracture resistance of ceramics [25], [26], [27], and therefore it should be used in order to better reproduce clinical circumstances. In addition, this study only examined the effect that endodontic access preparation has on milled lithium disilicate restorations (e.max CAD). Pressed lithium disilicate restorations (e.max Press) have not been studied, therefore the effect of accessing this type of restorations is currently unknown.

The fracture resistance of intact IPS e.max Press restorations has been examined. Stappert et al. were the first to evaluate the load to failure of IPS e.max Press onlay molar restorations. They reported mean fracture loads that ranged from 1,567 to 1,960N for the various groups, depending on the preparation characteristics of each group [28], whereas none of the specimens failed below 852N. Those values well exceeded the maximum biting force of approximately 720N for posterior single teeth reported in previous studies [29]. Their study simulated the oral environment by subjecting the specimens to mechanical loading using a mastication simulator and thermocycling. The same authors also compared different glass-ceramic systems available for the fabrication of onlay molar restorations and also to correlate fracture toughness of IPS e.max Press onlays with different preparation designs. In both studies, all specimens were subjected to thermomechanical loading, and the mean failure loads on both studies ranged from 1205N to 1489N. The lowest failure load recorded was 817N [30], [31].

Another study compared the fracture resistance of intact IPS Empress Esthetic and IPS e.max Press full-coverage molar restorations, after wet storage of the specimens for 1 week, cyclic loading and thermocycling. The mean failure loads that were reported for the IPS e.max Press restorations ranged from 3731N to 4173N, with a minimum load of 3006N recorded in the study [32]. This is the only published study reporting failure loads of full-coverage posterior restorations that have been fabricated using the IPS e.max Press system. Its results underlined the greatly improved mechanical properties of this material compared to previously used glass-ceramic systems.

As lithium disilicate crowns are becoming a commonly used restorative treatment modality, due to their enhanced mechanical and optical properties that are supported by the current literature, endodontic treatment and subsequent repair of the access opening will be a frequently encountered clinical challenge. The aim of this study was to evaluate how endodontic access preparation and subsequent repair may alter the fracture resistance of pressed and milled monolithic lithium disilicate crowns after fatigue testing (cyclic loading). It is known that simulation of the dynamic repetitive loading that occurs in the *in-vivo* environment will cause a decrease in the strength of the ceramic and lead to more clinically meaningful results [33, 34]. Additionally, this study aimed to examine the damage that occurred to the crowns once an endodontic access opening was completed. The null hypothesis was that there would be no difference in the fracture resistance between the intact and the accessed (and repaired) crowns, irrespective of their fabrication technique (pressed or milled).

2. MATERIALS AND METHODS

Twenty monolithic pressed lithium disilicate (IPS e.max Press) and twenty monolithic milled lithium disilicate (IPS e.max CAD) restorations were fabricated and adhesively bonded on identical epoxy resin dies. Following storage in saline solution for 3 weeks, ten crowns from each initial group were accessed for a simulated endodontic treatment. The accessed crowns were subsequently repaired with a porcelain repair system and all specimens were subjected to cyclic loading for a total of 250,000 cycles. After load to failure, force data were collected and analyzed. Additionally, four pressed and four milled restorations were fabricated in order to conduct an indicative SEM analysis and evaluate the surface defects caused by the procedure.

2.1 Master Die Fabrication

A wax pattern was fabricated to simulate a mandibular first molar all-ceramic complete crown preparation according to the manufacturer's recommendations for IPS e.max posterior crowns. The desired dimensions were a 12˚ total occlusal convergence, 8 mm diameter, 4 mm preparation height, a uniform reduction of 1.5mm on axial and occlusal walls and a 1-mm circumferential shoulder finish line with a rounded axiogingival angle. The pattern was subsequently sprued, invested and cast with chrome cobalt alloy (Vitallium, Dentsply, Woodbridge ON), in order to obtain a master die. An impression of the master die was made using high-strength silicon material and a high-heat epoxy resin (Viade Products Inc, Camarillo, CA) was poured into the impression. Twenty molds were created and each was poured twice resulting in 40 identical dies.

2.2 Crown Fabrication

The dies were then divided in two groups, P (Pressed) and M (Milled), each one consisting of 20 specimens.

2.2.1 Fabrication of pressed restorations

For group P, a standardized waxing was completed on each die, with a uniform thickness of 1.5mm. Before spruing and investing, a digital caliper was used to verify the thickness of each coping to within ±0.01mm. All copings were sprued with a 5-mm length of 10 gauge sprue wax in a 100 gram investment ring system (Silicon Ring; Ivoclar Vivadent). A second (blind) sprue was placed to ensure proper switch-off function of the pressing furnace once the pressing procedure was completed. Both sprues had a 45 degree angle to the base of the investment ring. Phosphate-bonded investment (IPS PressVEST Speed; Ivoclar Vivadent) was used to invest each individual waxing. After final setting of the material, each individual investment ring was preheated for 45 minutes at 1562°F. Twenty individual high-translucency ceramic ingots were used to produce 20 heat-pressed monolithic crowns using a pressing furnace (Vario Press 300, Zubler USA Inc., Irving, TX), according to the manufacturer’s recommendations. After cooling of the investments, the restorations were divested using polishing beads at 60psi pressure for the rough divestment and at 30psi pressure for the fine divestment. All crowns were fitted to their respective dies using fine diamond burs, keeping adjustments to the minimum, until marginal fit could be verified using an explorer and tactile sensitivity. IPS e.max Ceram Glaze Paste was then mixed with IPS e.max Ceram Glaze and Stain Liquid and one glaze firing cycle was completed, according to the manufacturer's recommendations. IPS Object Fix Putty (Ivoclar Vivadent) was used to stabilize the crowns during this procedure.

2.2.2 Fabrication of milled restorations

For group M, another standardized wax coping with the same dimensions as the ones used for group P was fabricated. The coping was then scanned with a CAD/CAM system which employs 3D laser technology (Straumann® Cares® Scan CS2) using the respective software (Straumann® Cares® Visual 8.0). The data obtained were used to produce 20 identical milled monolithic lithium disilicate restorations from IPS e.max CAD blocks of high translucency. After confirmation of proper fitting of the pre-sintered (blue stage) crowns to their respective dies, IPS e.max CAD Crystallization/Glaze Paste was mixed with IPS e.max Ceram Glaze and Stain Liquid and one combined crystallization/glaze firing cycle was completed, according to the manufacturer's recommendations. IPS Object Fix Putty (Ivoclar Vivadent), IPS e.max Crystallization Pins (Ivoclar Vivadent) and an IPS e.max CAD Crystallization Tray (Ivoclar Vivadent) were used to stabilize the crowns during this procedure, in order to avoid contamination with the glazing materials that were used for group P.

2.3 Crown Cementation

All forty crowns were steam cleaned, dried and then adhesively bonded to their respective dies, using the same procedure for each restoration. The intaglio surface of each individual crown was etched with 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 seconds. Following rinsing and drying of the etched surface, silanization was carried using the recommended universal primer (Monobond Plus, Ivoclar Vivadent) for 60 seconds. Remaining excess was then dispersed using oil-free air. Each die was etched with 37% phosphoric acid (Total Etch, Ivoclar Vivadent) for 15 seconds, and then rinsed and dried. Dual-curing, filled adhesive (ExciTE F DSC, Ivoclar Vivadent) was applied to the prepared surface of the die and pre-cured for 10 seconds with a LED Dental Curing Light (Demi, Kerr Co, Orange CA). A dual-curing resin based system for adhesive luting (Variolink II, Ivoclar Vivadent) was used to cement all restorations. The base and the low-viscosity catalyst pastes were mixed in a 1:1 ratio for 10 seconds and subsequently applied on the inner surface of the restoration. The crown was then seated to the die with finger pressure, excess cement was removed and polymerization was performed for 40 seconds at each side of the die (buccal, mesial, lingual, distal and occlusal) using a LED Dental Curing Light (Demi, Kerr Co, Orange CA). A uniform force of 50N was applied during light polymerization. Following cementation, all specimens were stored in a humid saline environment at room temperature for 3 weeks.

2.4 Endodontic Access Preparation

The specimens from each group were then further divided into two subgroups, with a total of 10 specimens in each subgroup: intact pressed monolithic crowns (PI), pressed monolithic crowns with a repaired standardized endodontic access preparation (PR), intact milled monolithic crowns (MI), and milled monolithic crowns with a repaired standardized endodontic access preparation (MR).

For groups PR and MR, a standardized, conservative endodontic access preparation with a diameter of 3.5mm was completed. The desired access opening was marked on the first specimen and after the preparation was completed, a plastic template was fabricated. This plastic template was used to delineate the access openings on all the crowns from groups PR and MR. All endodontic access preparations were performed by one clinician applying the same amount of force. The preparations were completed under copious water irrigation using an electric handpiece at 200,000rpm. The selected bur for this procedure was a coarse-grit (126µm) tapered round-end chamfer diamond (ZR6856.016; Komet, Besigheim, Germany) which has been ranked as the most efficient when cutting through lithium disilicate material[12]. For each access opening, a new bur was utilized.

2.5 Access Repair

Immediately after completion of all endodontic access preparations, the restorations were repaired using a porcelain repair system (Intraoral Repair Kit, Bisco Inc., Schaumburg IL) and a direct composite restoration, following the manufacturer's protocol. The area to be repaired was dried with oil-free air. Porcelain etchant (9.5% hydrofluoric acid) was applied on the porcelain surface for 90 seconds. After thorough rinsing and drying of the etched surface, one coat of porcelain primer was applied and allowed to dwell for 30 seconds. The repair site was dried again and a thin layer of porcelain bonding resin was applied. The repair was completed using nanocomposite resin (Filtek Supreme Ultra Universal Restorative, shade A2 enamel, 3M ESPE, Seefeld, Germany) which was applied in 2-mm increments, each polymerized for 40 seconds. The occlusal portion of the repair was made level with the adjacent lithium disilicate material and the interface was lightly smoothed using a rubber wheel under water irrigation.

2.6 Fatigue Test

All forty specimens were submitted to a fatigue test that consisted of cyclic loading in a dry state between minimum and maximum loads of 50 and 250N for a total of 250,000 cycles, using a servo hydraulic testing machine (858 Mini Bionix II, MTS

Systems Corp., Eden Prairie MN). The cyclic loading had a force profile in the form of a sine wave at a loading frequency of 1.6Hz and an axial loading direction.

After cyclic loading and before mechanical testing, each specimen was visually inspected for surface damage or cracking.

2.7 Mechanical Testing and Data Collection

All specimens were subsequently positioned in a universal testing machine (Instron Corp, Norwood, MA) and loaded along their long axis at a 0.2mm/min crosshead speed until failure. The loading piston was 6mm along its long axis and its end was pre-curved, thus eliminating high-contact stresses. The end of the piston was directed towards the center of the occlusal surface of each crown; for the repaired crowns, it was contacting both the composite resin repair as well as the surrounding lithium disilicate material. A room temperature was maintained throughout mechanical testing. A 1% drop in the compressive load and/or visualization of crack formation was designated as failure of the restoration. Force at the time of failure was recorded in Newtons (N).

After collection of the force data for all forty specimens, a statistical analysis was performed using a statistical software (SPSS 19.0; SPSS Inc., Chicago IL). Fracture strength was the dependent variable; the presence of a repaired endodontic access preparation and the method of fabrication (pressed vs. milled) were the independent variables.

The data were tested for normality using a Kolmogorov-Smirnov's test and for homogeneity of variances using a Levene's test. An analysis of variance (ANOVA) followed by a post hoc test (Sidak's correction) was used to indicate significant differences between the groups ($p<0.05$).

A Weibull analysis was also performed in order to calculate the Weibull parameters (modulus and characteristic failure load), and therefore compare the mechanical reliability of the four groups. The analysis was conducted using a life data analysis software (Weibull++, ReliaSoft, Tucson AZ). The same software was used in order to compare the load level of each group corresponding to a 5% probability of failure for the specimens belonging to that group.

2.8 SEM Analysis

Eight additional specimens (4 monolithic pressed, 4 monolithic milled) were also fabricated using the same methodology as the one followed for the specimens belonging to the initial groups P and M. Those specimens were then accessed for an endodontic treatment using the same protocol as the one followed for the twenty specimens from the groups PR and MR. After endodontic access, those crowns were coated with gold and examined under SEM. Micrographs were obtained in order to serve as an indicative example of the damage caused to the restorations by the procedure.

It was determined that if the original crowns were used for this SEM examination, then the sputter coating may have interfered with the porcelain repair protocol that would follow. Therefore, those additional crowns were fabricated, cemented on their respective dies and accessed for the sole purpose of completing an observation under SEM after the access opening was completed.

3. RESULTS

The load-to-failure data (mean ± standard deviation, as well as minimum and maximum load values) are shown in Table 1. The mean load to failure ranged from 1297N (group MR) to 1901N (group PI). The maximum load was observed in group PI (2554N) and the minimum load in group MR (882N).

Table 1. Descriptive statistics of load to failure (mean ± standard deviation) for the four groups.

	Pressed Intact	Pressed Repaired	Milled Intact	Milled Repaired
Sample size	10	10	10	10
Load to Failure (N)	1901 ± 349	1429 ± 384	1573 ± 267	1297 ± 329
Minimum (N)	1479	1128	1327	882
Maximum (N)	2554	2283	2094	1835
Kolmogorov-Smirnov*	P=.200	P=.069	P=.182	P=.200
Levene's Test**	P=.751			

* Test for normal distribution (P≤.05)

** Test for homogeneity of variances among the groups (P≤.05)

Table 2 shows the post-hoc analysis using Sidak's adjustment for multiple comparisons, which revealed a statistically significant difference between groups PI and PR (p=0.019), as well as between groups PI and MR (p=0.002). No statistically significant differences were found between groups MI and MR (p>0.05).

Table 2. Post hoc analysis for the load to failure for the four groups with Sidak's adjustment for multiple comparisons.

Multiple comparisons		**Significance**
Pressed Intact	Pressed Repaired	P=.019*
Pressed Intact	Milled Intact	P=.191
Pressed Intact	Milled Repaired	P=.002*
Pressed Repaired	Milled Intact	P=.919
Pressed Repaired	Milled Repaired	P=.945
Milled Intact	Milled Repaired	P=.367

* Indicates statistical significance

Even though a difference was noted between the fracture load for the group PI and those for all the other groups, this difference was not statistically significant. More specifically, no statistically significant differences were found between groups PI and MI or between groups PR and MR (p>0.05).

Visual inspection of all specimens after cyclic loading and before mechanical testing did not contribute to any significant observations, since no damage or surface cracking was noted on any of them.

The Weibull statistical analysis of the fracture load data is summarized in Table 3. The Weibull moduli for both intact groups (PI and MI) were higher than those of the repaired groups (PR and MR). The characteristic load for the group PI was the highest among all groups. However, none of those differences was statistically significant.

Table 3. Weibull parameters (modulus and characteristic load) for the four groups.

	Pressed Intact	Pressed Repaired	Milled Intact	Milled Repaired
Weibull modulus				
Estimate	5.9	3.9	6.3	4.5
Upper*	9.4	6.1	9.9	7.3
Lower*	3.7	2.5	4.0	2.8
Characteristic load (N)				
Estimate	2044	1572	1685	1421
Upper*	2285	1860	1870	1643
Lower*	1830	1329	1517	1229

* 95% confidence interval

A failure probability plot is presented at Figure 1, representing the load at or below which 63.2% of the specimens from each group are predicted to fail (characteristic load). The results indicated that specimens from the group PI are predicted to fail at much higher loads than any other group; however the differences were not statistically significant.

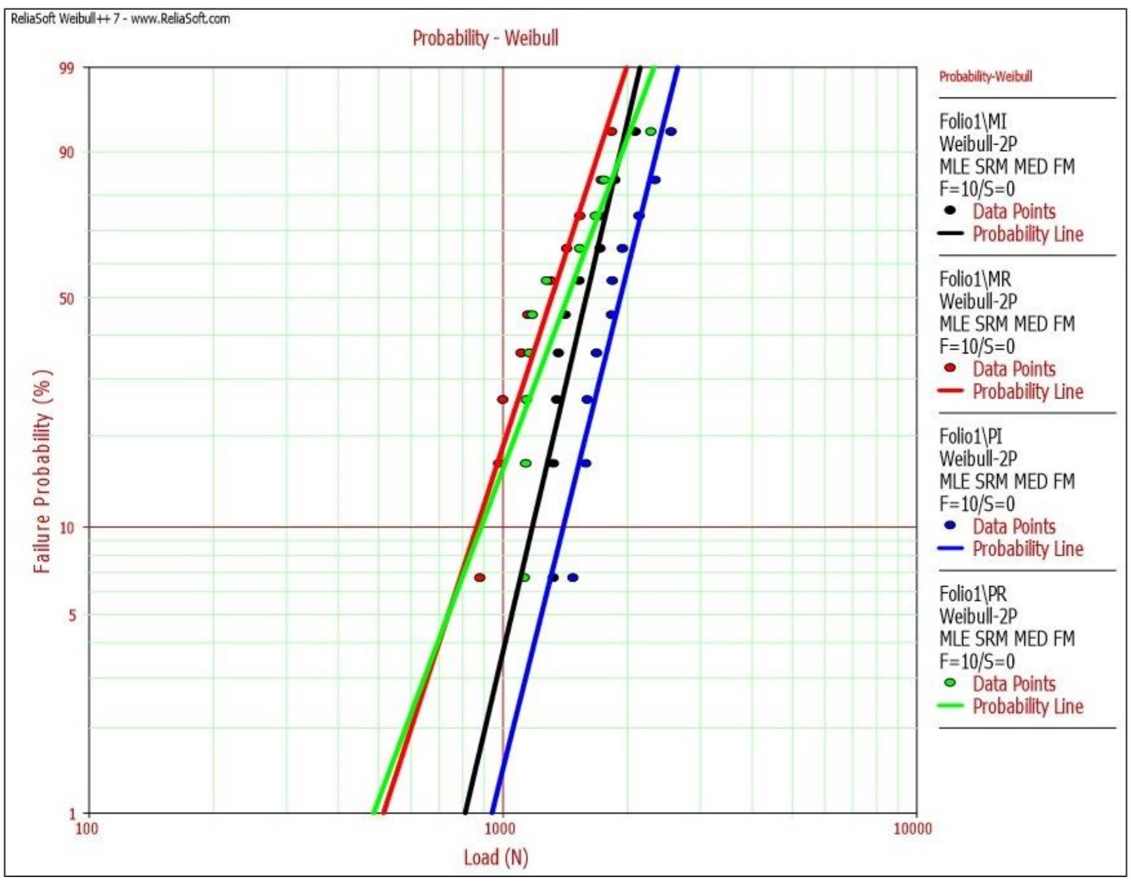

Figure 1: Failure probability plot for the four groups.

Finally, table 4 summarizes the point estimates and 95% confidence intervals corresponding to a 5% probability of failure. Group PI had the highest load value (1239N) and group MR the lowest (738N). Both 95% confidence intervals for the two repaired groups (PR and MR) included load values that were below the average occlusal force that is normally applied on a molar (720N).

Table 4. Point estimates (in N) and 95% confidence intervals corresponding to a 5% probability of failure for the four groups.

	Pressed Intact	Pressed Repaired	Milled Intact	Milled Repaired
Load Estimate (N)	1239	737	1050	738
Upper*	1652	1127	1377	1086
Lower*	929	483	802	501

* 95% confidence interval

3.1 SEM Analysis

All additional specimens that were examined under SEM showed edge chipping associated with the endodontic access preparations, extending radially from the openings. Chipping involved primarily the glaze layer, but was also extending up to

0.3mm into the occlusal portion of the lithium disilicate material on both pressed and milled crowns (figure 2). One of the chips on a milled crown was extending as a radial crack from the access up to 0.5mm from the proximal wall of the restoration (figure 3). This radial crack was readily detectible by visual inspection as well. No other radial cracks or microcracks within the internal microstructure of the material associated with the walls of the endodontic preparations were noted on any of the crowns.

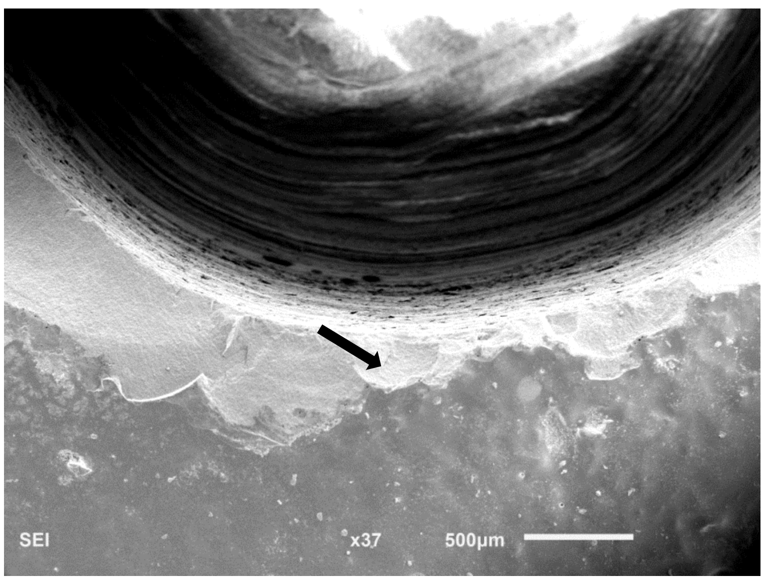

Figure 2: SEM of accessed pressed crown showing edge chipping extending radially around the access opening. Chipping involves primarily the glaze layer, but also extends into the superficial portion of the lithium disilicate material (pointing arrow). Original magnification x37.

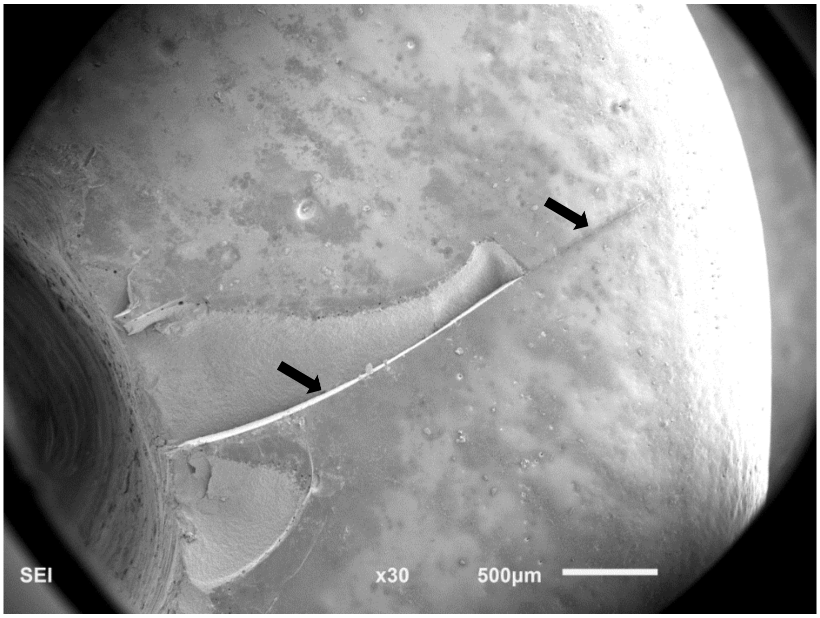

Figure 3: SEM of a milled crown showing radial crack formation extending close to the proximal wall of the restoration (pointing arrows). Original magnification x30.

The cross section of the internal surface of the milled crowns that were examined under the SEM, as it could be shown through the internal walls of the access preparations, appeared more irregular in comparison to that of the pressed crowns. As shown in figure 4, the internal surface of the milled restorations was less homogeneous than that of the pressed ones, which is shown in figure 5.

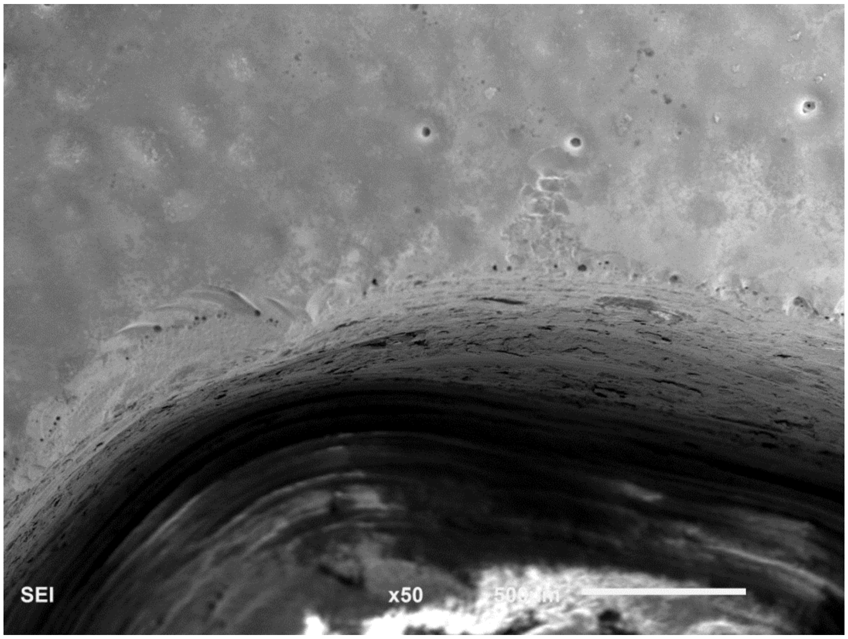

Figure 4: SEM of an accessed milled restoration. Internal microstructure reveals irregularities.Original magnification x50.

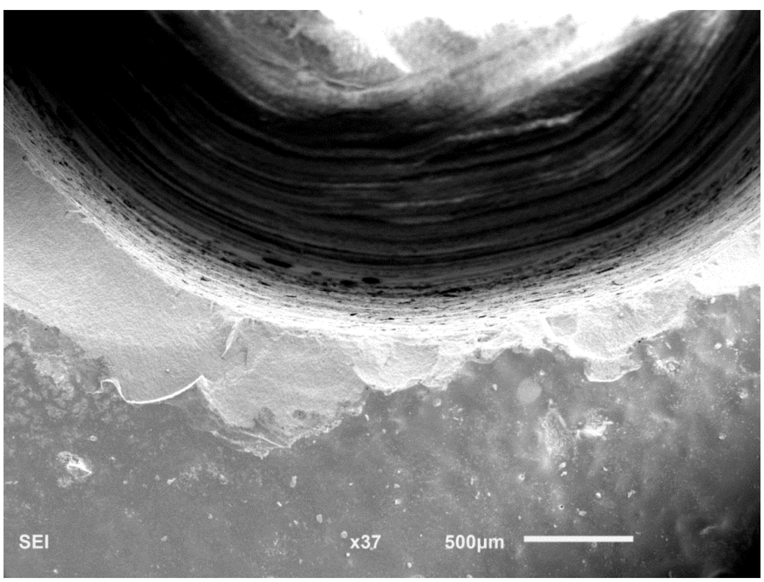

Figure 5: SEM of an accessed pressed restoration. Internal microstructure appears more homogeneous than that of the milled restorations. Original magnification x37.

4. DISCUSSION

The use of lithium disilicate restorations is markedly increasing, due to their excellent mechanical and esthetic properties. In the present study, mean load to failure for intact pressed restorations was significantly high (1901N), indicating that this type of restoration can safely withstand maximum intraoral masticatory forces. These results are in agreement with the ones reported by Stappert et al. for partial coverage IPS e.max Press restorations [28, 30, 31], but significantly lower than the ones reported by Clausen et al. for full coverage IPS e.mx Press restorations [32]. An explanation for this could be the difference in the preparation design used for the different studies, which leads to a different restoration geometry.

Mean load to failure for intact milled (IPS e.max CAD) restorations in this study (1573N) was in agreement with the findings of the study by Guess et al. [35], who evaluated fracture resistance of IPS e.max CAD full coverage monolithic restorations. Guess reported a threshold for damage/bulk fracture of IPS e.max CAD restorations at the range of 1,100-1,200N. This is again the only published study that examines fracture resistance of monolithic IPS e.max CAD full coverage restorations.

Pressed lithium disilicate (IPS e.max Press) restorations have been reported by the manufacturer to have higher fracture toughness compared to milled (IPS e.max CAD) restorations, and this was supported by the load to fracture values of the present study. However, the difference in fracture resistance between the two groups was not statistically significant, indicating that the method of fabrication is not a critical factor for the intraoral success of the material. Both IPS e.max Press and IPS e.max CAD full coverage restorations had fracture loads that were above the average biting force of 720N [29]. The lowest failure load recorded in this study was 882N, which is still above the average biting force. Similarly, there was not a statistically significant difference detected between the repaired pressed and the repaired milled crowns, indicating that the similarity between the mechanical properties of the crowns that were made using either technique does not change after subjecting them to a damaging clinical procedure. The mean fracture loads for both groups were still above the average occlusal force that is typically applied on a molar, indicating that repaired lithium disilicate restorations remain serviceable.

The null hypothesis of the study was that there would be no difference in the fracture resistance between the intact and the repaired crowns. This hypothesis was rejected for the pressed restorations, since there was a statistically significant difference between the load to failure for the intact (PI) and the repaired (PR) crowns. However, the results of this study failed to reject the null hypothesis for the milled restorations, since there was not a statistically significant difference between the load of failure for the intact (MI) and the repaired (MR) crowns. This finding can be attributed to the higher load to fracture values that were obtained for the pressed intact crowns, compared to those for the milled intact crowns. Repair of the crowns that were subjected to endodontic access preparation was able to restore the weaker milled crowns close to their original strength, but failed to do so for the stronger pressed crowns. These results are comparable to those reported by Wood et al.[23] , who found a significant decrease in strength for the repaired zirconia crowns, but not for the repaired alumina crowns. The authors attributed their findings to the higher initial fracture toughness of the zirconia crowns, compared to that of the alumina crowns. It can be therefore hypothesized that the stronger a material is when it is initially inserted in the mouth, the harder it will be to maintain these high mechanical properties once subjected to a damaging clinical procedure. Another factor to consider would be the difference in internal structure that was noted during the SEM analysis of the additional, representative restorations. The less homogeneous internal structure of the milled restorations may facilitate the formation of a bond between the lithium disilicate and the repair material, making it possible for the repaired restoration to achieve higher loading values that can even approximate those of the intact restorations belonging to this group.

The Weibull analysis showed that endodontic access preparation and subsequent repair affected the reliability of both IPS e.max Press and IPS e.max CAD restorations. The Weibull moduli for both intact groups were higher than those of the repaired groups, indicating higher material homogeneity and therefore lower probability of failure for specimens belonging to those two groups. This was an expected finding, since the procedure of accessing the crown would introduce more flaws in the material. Since it is well documented that strength of dental ceramics is primarily flaw-dependent, any procedure that introduces microcracks within the internal structure of the material could accelerate long-term failure of the material.

The Weibull analysis included comparing the characteristic load for the four groups, which corresponds to the load value below which 63.2% of the specimens are predicted to fail. As was shown in figure 1, the specimens belonging to group PI were likely to fail in loads that were much higher than the loads for the other three groups; however, none of these differences was statistically significant. Further analysis of the load estimates and 95% confidence intervals corresponding to a 5% probability of failure was conducted for all groups. A comparison at this level may result in some loss of statistical power, but it provides more clinically relevant data. The results show that there is a significant difference between the load values below which 5% of the specimens will fail for the intact groups (1239N for IPS e.max Press and 1050N for IPS e.max CAD restorations) compared to the repaired groups (737N for repaired IPS e.max Press and 738N for repaired IPS e.max CAD restorations). Therefore, the analysis at this level showed that there was a significant difference in the fracture resistance before and after the endodontic access preparation and subsequent repair of the crown. It was also noted that the load corresponding at a 5% probability of failure was the same for both repaired groups (737N for IPS e.max Press and 738N for IPS e.max CAD). These results indicate that IPS e.max Press may yield a stronger initial restoration compared to IPS e.max CAD; however, once this restoration is subjected to a damaging clinical procedure, such as endodontic access preparation and repair, the toughness of the repaired material will drop at the same levels as the toughness of the repaired IPS e.max CAD restoration, even though the latter was initially weaker.

A final factor that needs to be considered in the attempt to present a possible repair protocol for monolithic lithium disilicate full coverage restorations is the feasibility of bonding of the repair material with the lithium disilicate core [13-19]. Only one study has been published that investigates the effect of different surface pretreatments on the bond strength between IPS e.max lithium disilicate restorations and composite resin repair material [14]. The authors concluded that treatment of IPS e.max CAD surfaces with hydrofluoric acid and silane prior to repair was superior to sandblasting the ceramic surface with aluminum oxide, which should be avoided in clinical practice. A limitation of this study was the absence of a control group with no surface treatment, or with application of silane only or hydrofluoric acid only as different treatment methods, in order to indicate the real effect of hydrofluoric acid and silane application on bond strength between lithium disilicate and composite resin. This study did not include any IPS e.max Press restorations either. Since repair of all-ceramic restorations is a commonly encountered clinical situation and its occurrence will only increase in the future as those restorations become more frequently fabricated, more studies are needed in this area in order to aid in the establishment of the most appropriate repair protocol.

In our study, the specimens were round and symmetric, without the incline planes and all the shape variations that are existent in natural teeth. However, even in natural teeth with normal occlusal morphology, loading should have an axial rather than an oblique direction and this should always be kept in mind while delivering and monitoring any posterior restoration. Therefore, the absence of cusps and occlusal anatomy on the specimens was not considered to be a limitation of the study, since it represents an ideal clinical loading situation. On the other hand, different loading directions may occur if proper adjustments are not completed and may have a different effect on the results.

Cyclic loading under dry conditions is one of the limitations of this study. While wet storage and dry cyclic loading reduce the failure loads of all-ceramic restorations, the presence of water during cyclic loading has been reported to produce failure loads that are more meaningful from a clinical standpoint. The specimens were also stored in saline, whereas the dynamic oral environment may have a further negative impact on the aging of the ceramic.

Even though this study followed as closely as possible the recommendations for testing ceramics as proposed by Kelly [33, 34], there are still some potential improvements that can be suggested. Future studies could evaluate the effect of endodontic access preparation and subsequent repair on bilayer lithium disilicate crowns, in order to detect possible differences in the mechanical behavior between the repaired monolithic and the repaired bilayer lithium disilicate restorations. Another enhancement to the study could be the cyclic loading under wet conditions, in order to better represent the oral environment and provide even more clinically meaningful results. Finally, SEM analysis of a larger group of accessed crowns could reveal more detailed information regarding the type and extent of damage created to the crowns during endodontic treatment.

5. CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions can be drawn:

1. Fracture resistance of intact pressed lithium disilicate (IPS e.max Press) restorations was higher than that of intact milled lithium disilicate (IPS e.max CAD) restorations.
2. Endodontic access preparation of lithium disilicate restorations resulted in a significant decrease in the fracture resistance of the pressed (IPS e.max Press) specimens, but not in the milled (IPS e.max CAD) restorations.
3. Endodontic access preparation resulted in edge chipping around the access openings of all crowns in the glaze layer (IPS e.max Ceram).
4. The fracture strength values for all groups were higher than the previously published clinical masticatory forces that can be present at the molar area.

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