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RESEARCH ARTICLE

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Tooth-cusp preservation with lithium disilicate onlay restorations: A fatigue resistance study

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Abstract

Objectives: This study examined the in vitro fatigue resistance of maxillary premolars with 2 mm or 3 mm preserved cusp thicknesses restored with lithium disilicate onlays.

Materials and Methods: Premolars(N = 48) were divided into six groups. Onlays for groups 1 to 4 preserved a 3 mm functional (G1), 2 mm functional (G2), 3 mm nonfunctional (G3), or 2 mm nonfunctional (G4) buccal-lingual cusp width. Onlays for group 5 (G5, control) replaced both cusps. Group 6 (G6) samples were identical to G1 with added retentive boxes. Lithium disilicate onlays were exposed to thermocycling (10 000 cycles, 5°C-55°C, 30s/cycle) and mechanical loading (1.2 million cycles at 1.4 Hz and 70 N). All samples were examined for onlay debonding or cusp or onlay fracture.

Results: Failure rates were 75%(G1), 0.0%(G2), 12.5%(G3), 0.0%(G4), 0.0%(G5), and 0.0%(G6). The difference in percent failure between the groups preserving the functional cusps (37.5%) and the groups preserving the nonfunctional cusps (6.3%) was statistically significant (P = .04; 95%CI:2.11-55.66). No cusp or restoration fractures were observed; all failures were due to debonding of the restoration.

Conclusion: Teeth with thin remaining cusps that were restored with bonded lithium disilicate onlay restorations were not prone to fracture. Retentive preparation features that physically eliminated lateral displacement prevented onlay debonding even though the ceramic-enamel margin was directly at the occlusal contact.

Clinical significance: The use of adhesively retained lithium disilicate ceramic onlays may be a viable alternative to full coverage restorations and may challenge traditionally accepted principals related to preparation resistance and retention form of ceramic partial coverage restorations.

KEYWORDS
CAD/CAM, ceramics, digital dentistry, operative dentistry, prosthodontics

1 | INTRODUCTION

Modern operative dentistry has experienced a dramatic rise in minimally invasive restorations. Clinicians routinely challenge traditional guidelines for preparation/restoration design with the goal of conserving as much tooth structure as possible. Further, the development of reliable enamel and dentin adhesive techniques and ceramic materials with improved physical properties has led to a significant increase in the utilization of ceramic restorations.[1]

In addition to the rising cost of noble metal alloys, the development of posterior adhesive restorations has been fueled by the growing demand of patients for esthetic and metal-free restorations. Using "tooth-like" restorative materials, such as composite and ceramic, in combination with bonding to enamel and dentin supports the overall goal of restorative dentistry, which is essentially to mimic and recover the biomechanics of the original tooth.

In alignment with this clinical philosophy, ceramic onlays are now considered viable alternatives to complete coverage crowns, with greater than 90% success at 10 years.[2] The etchable glass ceramic, lithium disilicate (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein), may be used in chairside CAD/CAM fabrication of restorations, including onlays. Investigations have shown excellent biomechanical characteristics, including a high flexural strength of ≅400 MPa.[3] A retrospective clinical research study by Fabbri et al reported cumulative survival rates of lithium disilicate onlays ranging from 97.86% to 100% over an observational period of up to just under 5 years.[4] The authors, therefore, suggest that lithium disilicate may be a reliable material for ceramic onlays. However, the manufacturers fail to provide guidelines as to when cuspal coverage with the ceramic material is indicated.[5]

Research studies focusing on cuspal coverage indications using modern restorative materials are sparse. Bulk fracture and loss of restoration have historically been reported to be the main reasons for clinical failures of inlays and onlays.[6-9] Lithium disilicate ceramic however, with its improved mechanical durability, as compared with other etchable glass-ceramics, may offer increased clinical longevity for partial coverage restorations.[10-12]

The few published research studies that evaluated the effect of remaining cusp thickness on fracture rates did not use lithium disilicate ceramic onlays. Additionally, these research studies did not compare possible differences in preparation design of the functional vs nonfunctional cusps.[13,14] Traditional onlay preparation guidelines suggest to "cap a cusp if the extension is two-thirds or greater than the distance from any primary groove to the cusp tip".[15] These protocols were based on the 1981 classic research study by Larson et al which concluded that restorations that encompass just one-third of the intercuspal distance reduce the tooth's resistance to fracture by more than 50%.[16] However, these recommendations were based in the era when metal alloys were used, and only aqueous-based luting agents existed. Even though both ceramic and adhesive technology now exists, textbook recommendations for onlay preparations remain the same.[15] Therefore, the overall objective of this study was to examine the in vitro fatigue resistance of restored premolars with varying preserved cusp widths, and to determine if functional and nonfunctional cusps have different cuspal coverage indications.

2 | MATERIAL AND METHODS

Forty-eight freshly extracted human maxillary premolars free of caries, cracks, endodontic treatment or restorations, were selected. Tooth surface calculus and soft tissue were removed with a hand scaler. Specimens were stored in 0.05% thymol solution @ 25°C for 1 to 2 months prior to use and randomly divided into six groups of eight specimens each. Two calibrated operators (E.G. and I.A.) prepared teeth one group at a time. Preparations were performed with 330MWV, 846KR.31.016 M, and 8846KR.31.016F diamond modified flat-end taper burs (Brassler, Savannah, GA) in an air-turbine high-speed handpiece operating at ~200 000 rpm with copious air and water-cooling.

Each group was prepared for an onlay restoration design that replaced one cusp and a varying buccal-lingual width of the remaining cusp (Figure 1-F). Preserved cusp buccal-lingual width was verified with a digital caliper (63 731, Pittsburgh Pro, Pittsburgh, PA) at the base of the remaining cusp. Remaining preparation measurements were verified with a periodontal probe. Preparations were designed to simulate the clinical presentation of a fractured cusp with a previous MOD restoration. Since the average distance between functional and non-functional cusp tips of maxillary premolars is ~5 mm and the facio-lingual diameter is ~9 mm, it may be that ≥2/3rds loss of a cusp would leave remaining cusp thickness of ~2 to 3 mm.[17] Therefore, standardized tooth preparations were completed as follows:

- Group 1 (G1): Preparation of each maxillary premolar was initiated by a 2.0 mm depth cut mesio-distally through the central groove. The preparation was extended laterally to the facial to completely and horizontally reduce the nonfunctional cusp, and preserve 3.0 mm of the buccal-lingual width of the functional cusp. This created an approximate 3.0 mm pulpal depth from the occlusal cavosurface margin of the functional cusp. A 1.0 mm wide rounded shoulder margin was placed 1.0 mm above the cementoenamel junction (CEJ) surrounding the completely reduced non-functional cusp.
- Group 2 (G2): Initially prepared identically to Group 1, while preserving 2.0 mm of the bucco-lingual width of the functional cusp.
- Group 3 (G3): Initially prepared identically to Group 1, while preserving 3.0 mm of the bucco-lingual width of the non-functional cusp.
- Group 4 (G4): Initially prepared identically to Group 1, while preserving 2.0 mm of the bucco-lingual width of the non-functional cusp.
- Group 5 (G5, control): Complete cuspal coverage. Preparation of each maxillary premolar was initiated by a 2.0 mm depth cut through the central groove. The preparation was extended laterally to reduce both the functional and nonfunctional cusps by approximately 2.0 mm. A 1.0 mm wide rounded shoulder margin was placed 1.0 mm above the CEJ.
- Group 6 (G6): Premolar preparation was initially identical to Group 1 and, subsequently, two 1.5×2.0 mm retentive boxes were placed 1.0 mm above the CEJ on the mesial and distal surfaces.

CAD/CAM blocks of lithium disilicate (IPS e.max CAD A2 LT, Ivoclar Vivadent, Schaan, Liechtenstein) were used in conjunction with CEREC BlueCam (Dentsply Sirona, Charlotte, NC, USA) using software version 4.4.4 to fabricate test sample onlays. The software "biogeneric

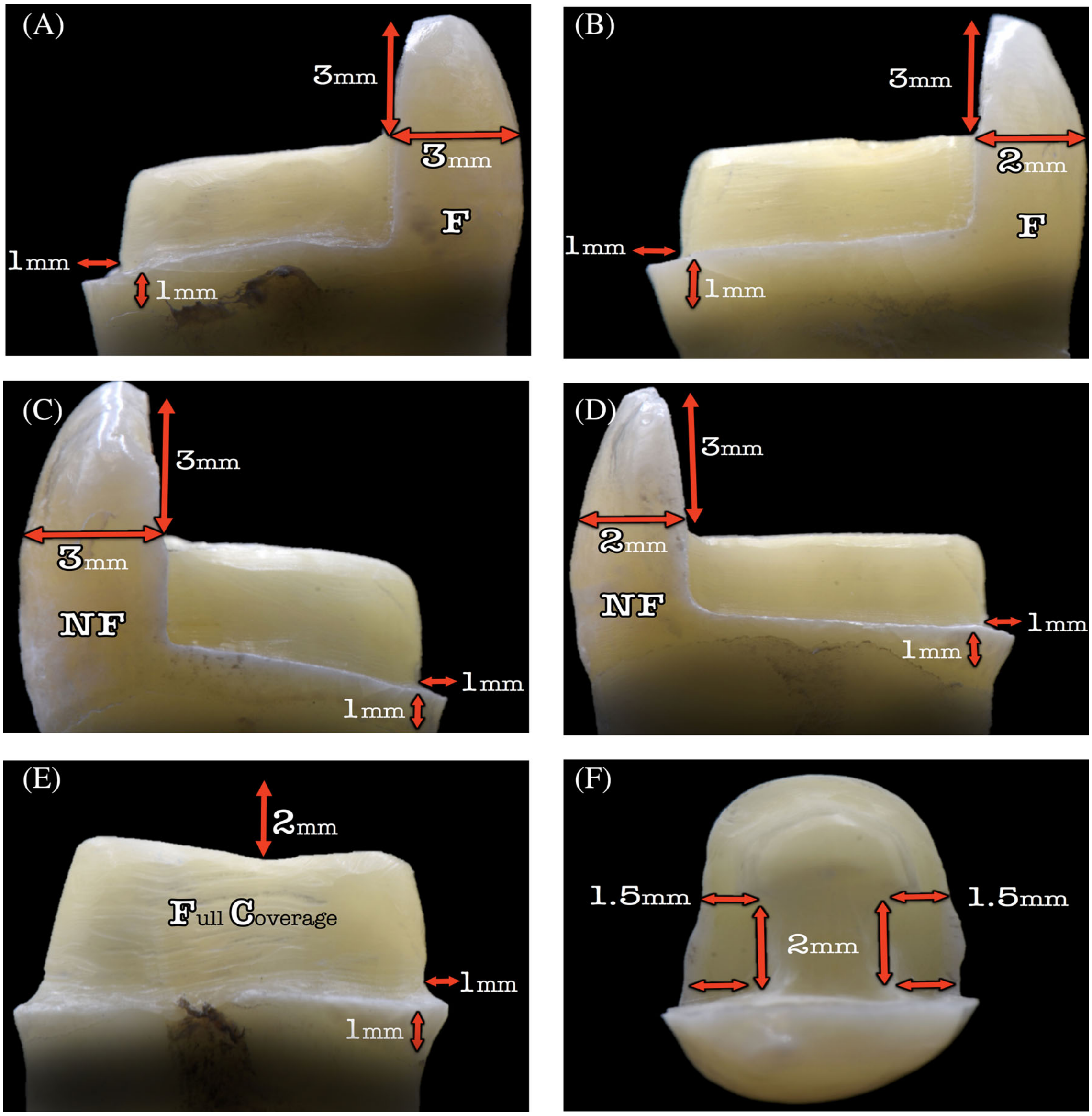

FIGURE 1 A, Group preparation designs; Group 1. B, Group preparation designs: Group 2; C. Group preparation designs: Group 3; D, Group preparation designs: Group 4; E, Group preparation designs: Group 5; F, Group preparation designs: Group 6 with added retentive mesial and distal boxes

copy" function was utilized to replicate the original anatomy of the tooth in the onlay restoration. Therefore, because of the standardized tooth preparations, minimal occlusal thickness of the onlays was 2.0 mm and minimal axial thickness was 1.0-1.5 mm. Onlays were crystallized according to the manufacturer's instructions using Object Fix putty (Ivoclar Vivadent, Schaan, Liechtenstein) and the Programat CS2 furnace (Ivoclar Vivadent, Schaan, Liechtenstein). IPS e.max CAD Crystall Glaze Spray was applied prior to crystallization according to manufacturer's instructions. Monobond Etch and Prime (Ivoclar Vivadent, Schaan, Liechtenstein) was used to prepare the intaglio surface of onlays, which were bonded with Variolink Esthetic DC (Ivoclar Vivadent, Schaan, Liechtenstein) resin cement following selective etching of the enamel with 37% phosphoric acid and Adhese Universal (Ivoclar Vivadent, Schaan, Liechtenstein) to the dental tissues according to the manufacturer's instructions. Excess luting material was removed, and glycerin gel was applied to the resin cement margin prior to final curing. Onlays were light cured for 20 s per surface (Demetron A.2 L.E.D. Curing Light, Kerr, Orange, CA) with consistent measured light output of 1000mw/cm^2, the irradiance of the light curing unit was measured using the MARC Light Collector (BlueLight Analytics, Halifax, NS, Canada) to ensure the consistency of polymerizing conditions. Samples were stored in 37°C deionized water for 48 hours after bonding ceramic onlays to prepared teeth.

Test specimens were prepared for fatiguing in a chewing simulator (SD Mechatronik, Feldkirchen-Westerham, Germany). Specimens were oriented parallel to the long axis of the tooth and embedded in acrylic resin (VariDur 200, Buehler, Lake Bluff, IL) from the root to

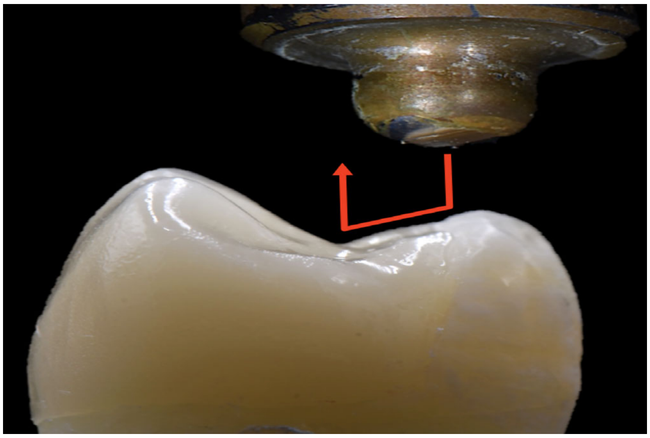

FIGURE 2 Mechanical loading pattern of stainless-steel antagonist

1.0 mm below the CEJ in the cylinder specimen holders of the chewing simulator.

Each group was exposed to simultaneous thermocycling (10 000 cycles, 5-55°C, 30 s dwell time/cycle) and mechanical loading (1.2 million cycles, 70 N/cycle, 1.4 Hz). A 4.0 mm diameter stainless-steel antagonist was used to represent an opposing cusp. During each mechanical loading cycle the stainless-steel antagonist contacted the functional cusp, then moved laterally across the occlusal surface to the central fossa (Figure 2). The antagonist did not come into contact with the nonfunctional cusp tip, only the adjacent triangular ridge. A 1.0 mm vertical indentation threshold facilitated constant occlusal surface contact while the antagonist moved horizontally across the occlusal surface.

Failure was defined as catastrophic fracture of the restoration/tooth, similar to what would be considered a failure clinically. Additionally, debonding of the restoration was considered a failure. Each specimen was monitored by a wear detector, mounted in each chamber of the chewing simulator throughout the fatiguing cycle. If the wear detector detected an abnormally large change in the height of a specimen (indicating a large fracture or restoration debonding), the cycle number was recorded, and the specimen was removed from the chewing simulator. After testing was complete, further visual examination with ×2.5 magnification loupes using normal operator illumination was used to detect additional fractures or chipping of the tooth or onlay.

The influence of cusp type was analyzed with the test of proportions by comparing the cumulative percent failure of the functional cusp groups (G1 + G2) with the cumulative percent failure of the nonfunctional cusp groups (G3 + G4) at a 4% significance level.

3 | RESULTS

The failure rates were as follows: 75.0% (G1), 0.0% (G2), 12.5% (G3), 0.0% (G4), 0.0% (G5), and 0.0% (G6) (Table 1). The restorations debonded for Group 1 in cycles 120 000, 297 000, 297 000, 765 000, 960 000, and 1 150 000 cycles. For Group 3, the restoration debonded at cycle 480 000 (Figure 3). No other specimen failures (as previously defined as catastrophic failure) were detected after visual inspection with loupes.

TABLE 1 Test group failure rates and cumulative survival rates

Groups	Failures	Failure Rate	Cumulative survival rate
G1- 3mmF	6	75.00%	37.5%*
G2- 2mmF	0	0.00%	
G3- 3mmNF	1	12.50%	6.3%
G4- 2mmNF	0	0.00%	
G5- FC	0	0.00%	-
G6- 3mmF w/ R	0	0.00%	-

Abbreviations: F, functional; NF, nonfunctional; R, retention; FC, full crown.

*statistically significant difference between the functional cusp groups and nonfunctional cusp groups (*P* = .04).

The cumulative failure rate for the functional cusp groups (G1 + G2) was 37.5%. The cumulative failure rate for the nonfunctional cusp groups (G2 + G3) was 6.3%. The difference in percent failure between the functional cusp groups and nonfunctional cusp groups was statistically significant (*P* = .04; 95%CI:2.11-55.66). Groups 2, 4, and 5 experienced no specimen failures. Group 6, which was identical to Group 1 with the addition of retentive mesial and distal boxes, also experienced no failures.

Overall, no cusp or restoration fractures were observed. After visual inspection, all failures were determined to be solely from debonding of the restorative onlay. The failures were both adhesive and cohesive in nature.

4 | DISCUSSION

The use of adhesively bonded ceramics may be advantageous in clinical scenarios where traditional mechanical retention form is limited and may allow for more conservative tooth preparations. In these cases, the need for conventional means of retention may be reduced due to the bonding potential of ceramic to dentin and enamel with composite resin cement.[18] The success of these partial coverage ceramic restorations is, to a high degree, dependent on sufficient support and an optimal adhesive bond to the underlying tooth structure.[14] The resin cement attachment to underlying tooth structure may reinforce the intaglio surface of the ceramic and limit crack initiation/propagation, maximizing its potential strength.[19-22] The adhesive attachment is a major advantage in the use of bonded ceramic onlays, in that they may be used in cases with minimal retention to conserve healthy tooth structure. The minimal preparation for the bonded ceramic partial coverage restoration is less traumatic for the tooth, and pulp vitality may be preserved.

The clinical performance of adhesively bonded all ceramic restorations has mostly been studied in the short- and medium-term. There

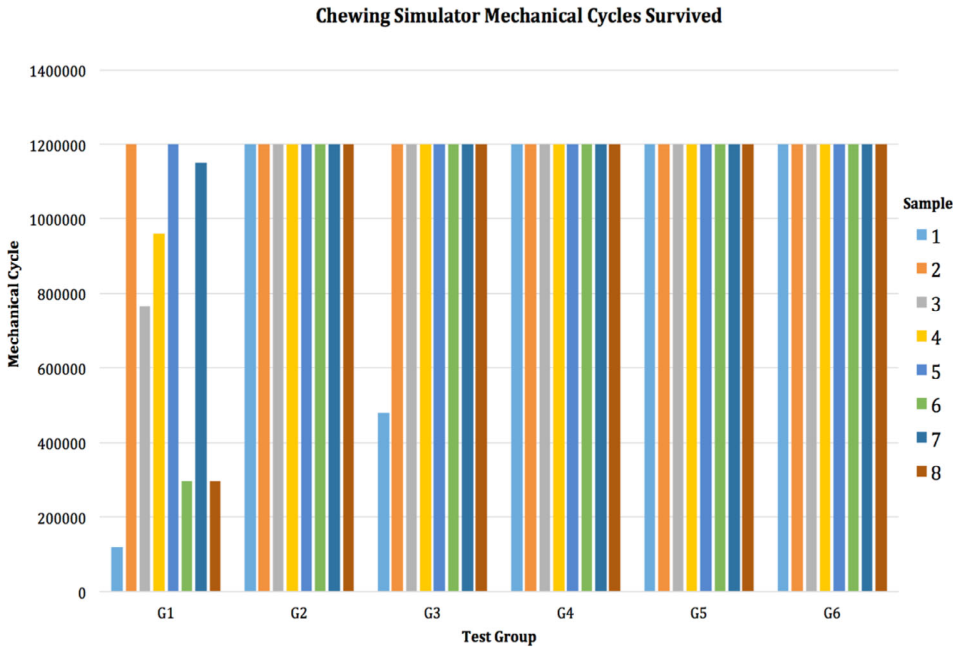

FIGURE 3 Mechanical cycles survived (or detected failure cycle) for each test specimen

are few studies with extended observation periods of 10 years or more. Frankenberger et al found the failure rate for IPS Empress (leucite-reinforced feldspathic porcelain) inlays and onlays of 12% at 12 years, mostly due to bulk fracture.[7] Van Dijken and Hasselrot conducted a 15-year evaluation of extensive dentin-enamel bonded IPS Empress partial and complete coverage restorations. In the clinical trial, the authors included onlays that preserved very thin portions of buccal or lingual cusps. Overall, the cumulative failure rate was 24% after 15 years. Most of the failures were due to restoration loss or fracture, with only 1 tooth in the entire study experiencing a cusp fracture.[8]

To the best of the author's knowledge, no long term, randomized controlled clinical trials that evaluate lithium disilicate's use for onlay restorations have been published. In an effort to evaluate the clinical performance of lithium disilicate ceramics, there have been two studies that sought to indirectly gain insight into restoration longevity by analyzing dental laboratory data from dentists making remake requests. One study showed 0.99% of IPS e.max onlays were requested to be remade due to fracture over 4 years.[23] The second study reported 0.70% of IPS e.max CAD onlay restorations be remade after 3.5 years due to fracture.[24] Although these studies do not replace the need for long-term randomized controlled clinical trials, they do potentially suggest that in the medium-term, lithium disilicate onlays do not experience a high rate of catastrophic failure.

Ideal preparation design standards for dentin-enamel-bonded crowns or partial coverage restorations are lacking. A common clinical dilemma regarding inlay and onlay restorations relates to cavity design. Specifically, there is confusion amongst dentists regarding occlusal isthmus width, remaining cusp thickness, and when cuspal coverage is indicated. The traditional principals of cavity preparation with respect to cuspal coverage are based on cast metal or amalgam restorations that do not adhere to the dental tissue.[15,16,25]

A few in vitro studies suggest that the use of adhesive techniques may provide cuspal reinforcement and enhance fracture resistance of nontraditional onlay preparation designs.[22,26,27] The present study demonstrated the high fatigue resistance of adhesively bonded onlay restorations. Additionally, unlike the previously mentioned studies, this experiment sought to more closely mimic clinical conditions by exposing samples to simultaneous thermocycling and mechanical loading, thus creating an environment where ceramic is typically more at risk of fatigue failure.[28-30] The samples in this study were exposed to 1.2 million cycles, an equivalent to five clinical years.[31] The 3D motion of the teeth during chewing simulated vertical as well as lateral loading. A limitation of this study is that only lateral forces occurred on the nonfunctional cusp as the antagonist moved into contact with the triangular ridge. This lateral force on the nonfunctional cusp may have significantly contributed to the sole mode of failure observed: debonding of the onlay. However, the use of lateral movements on restorations has a deteriorating effect, especially in wet environments. Therefore, it is recommended that any laboratory simulation intended to establish the longevity of an all-ceramic restoration include lateral movements to resemble clinical oral conditions more closely.[32,33]

In the present study, human maxillary premolars were used to prepare samples, making it difficult to standardize the preparations perfectly given slight differences in the shapes of the natural teeth. Accordingly, because the “biogeneric copy” function was used to generate the onlay design, there were slight differences in the final shapes of the onlays. The calibrated operators verified preparation parameters with a periodontal probe, which may not have been thoroughly accurate. However, the CEREC software was used to verify minimal restoration thickness of at least 1.5 mm. Nonetheless, no restoration fractures were observed in this experiment.

No association was found between the fatigue resistance of premolars restored with CAD/CAM lithium disilicate onlays and the preserved buccal-lingual wall width of the remaining cusps since there were no bulk cusp or restoration fractures. Notably the nonfunctional cusps, which were exposed to a high degree of lateral forces when the stainless-steel antagonist rotated to the central fossa, did not experience any fractures. There was a detectable statistically significant difference in the failure rates (due solely to restoration debonding) between the groups that preserved the functional cusp and the groups that preserved the nonfunctional cusp. Although enamel margins were preserved in this study, the bond strength between dentin and resin adhesive will deteriorate over time and with cyclic loading.[34,35] However, the debonding failures seen may be attributed to the stainless-steel direct contact on the functional cusp/ceramic margin and the following lateral force it posed to the nonfunctional triangular ridge. Both of these variables encouraged debonding of the restoration.

G1 displayed the highest failure rate of 75.0%. The stainless-steel antagonist made occlusal contact on the marginal interface between the preserved functional cusp and the restoration in this group (Figure 3). Magne et al studied premolar cuspal flexure as a function of restorative material and occlusal contact location. It was found that antagonist contact with the restoration margin demonstrated the most amount of cuspal deformation.[36] In the present study in addition to the significant lateral forces, the high rate of onlay debonding in G1 may have also been caused by antagonist forces directly contacting the restoration margin on the functional cusp with resultant cuspal deflection and/or sheer stresses at the adhesive interface. G6 preparation design was identical to G1, with added mesial and distal boxes for retention/resistance. Remarkably, this group demonstrated a 0.0% failure rate. Although the antagonist also made contact with the restoration margin in this group, the added vertical walls may have minimized movement of the onlay away from the cusps, thus preventing the onlays from debonding. The presence of box-like retention forms may have limited the ability of shear forces to overcome the adhesive interface. In addition, creation of retentive boxes increased surface area available for bonding. Therefore, a clinician may want to consider adding retention/resistance form to an onlay preparation design if the opposing occlusion will contact the restoration margin. In G2, a 2.0 mm buccal-lingual width of the functional cusp was preserved in each sample. This design allowed for the antagonist to make majority contact with the onlay restoration, and not the onlay margin or remaining cusp. This group demonstrated a 0.0% failure rate. Not surprisingly, these findings are in support of the traditionally held guiding principle that placement of direct or indirect restoration margins should not occur at the region of occlusal contact. The increased failure rate of G3 (12.5%), as compared with G4 (0%), may be a result of a smaller surface area of bonding (the remaining non-functional cusps were 3 mm in contrast to the 2 mm G4 non-functional cusps). Alternatively, since 12.5% actually represents the debonding of only 1 out of 8 onlays in G3, this finding may be secondary to dentin variability and/or some type of compromise during development of the adhesive interface.

There was a statistically significant difference in the cumulative failure rates between the functional (G1 + G2) and nonfunctional (G3 + G4) cusp groups ($P = .04$). It is important to note again that none of the failures in this study was due to cusp fracture although, clinically, functional cusps are generally subject to more compressive forces while nonfunctional cusps tend to receive more tensile forces.[37] This difference among the functional and non-functional groups though detected, was not related to remaining cusp thickness, but rather related to surface area for bonding (as seen in the comparison of G3 & G4) or, as noted above, compromise secondary to dentin variability or technique since it represents only one restoration out of a small group. The mechanism of restoration failure in the functional cusp group was most likely related to the margin location in relation to antagonist occlusion, as previously discussed. Although 2 mm cusps were preserved in groups 2, 3, and 4, the antagonist occlusion was not directly on the restoration margin and only one restoration debonded (G3). In addition, there were no restoration fractures. This result is consistent with the most recent laboratory data, which concluded that the fracture rate of lithium disilicate onlay restorations is extremely low, 0.99% at 7.5 years.[38] Mixed Cohesive and adhesive failure modes were recognized by the examiner, however not recorded due to the low magnification used for analysis (×2.5). Future studies should consider use of a scanning electron microscope to categorize failure mode as well.

The conservative preparation designs used in this study may, in theory, minimize the risk of pulpal complications in vital teeth. In addition, other advantages may include preserving more of a tooth's natural anatomy, color, and occlusal relationships. The use of adhesively retained lithium disilicate ceramics, that demonstrate improved biomechanical properties for partial coverage restorations, may be a viable alternative to full coverage restorations and may challenge traditionally accepted principals related to preparation resistance and retention form.

5 | CONCLUSION

Within the limitations of this study, teeth with thin remaining cusps that were restored with bonded lithium disilicate onlay restorations were not prone to fracture. Retentive preparation features that physically eliminated the potential for lateral displacement of the onlays prevented debonding even though the ceramic-enamel margin was directly at the occlusal contact. Conventional onlay preparation guidelines should be challenged in favor of preparation designs, which preserve more of the natural tooth when utilizing bonded lithium disilicate onlays.

DISCLOSURE

The authors do not have any financial interest in the companies whose products or devices are included in this article.

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