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Abstract

Objective: To analyze the significance of axial wall height in restoration retention involving adhesively-bonded CEREC e.max® CAD crowns on preparations with moderate total occlusal convergence (16 degrees).

Methods: 60 recently-extracted maxillary third molars were randomly divided into 5 groups (n = 12) and prepared for full-coverage, all ceramic restorations with occlusal cervical (OC) axial wall heights of 0,1,2,3, and 4mm, all with a moderate total occlusal convergence (TOC) of 16 degrees. Completed preparations had preparation features confirmed and dentin surface area for adhesive bonding determined using a digital measuring microscope (Hirox). Scanned preparations (CEREC®) were fitted with a lithium disilicate restoration with a self-adhesive resin luting agent after intaglio surface preparation with hydrofluoric acid and silanation. All manufacturer recommendations were followed. Specimens were stored at 37C/98% humidity for 24hrs and tested to failure at a 45-degree angle applied to the palatal cusp on a universal testing machine. Mean results were analyzed using ANOVA/Tukey's (p=0.05).

Results: Failure load results found a higher resistance to dislodgement and similarity with the preparations containing 2, 3, and 4 millimeters of ferrule, which was greater than the preparations containing one and zero OC ferrule. However, calculated failure stress found all groups to be statistically similar.

Conclusions:

Under the conditions of this study, molar preparations containing a 16 degree TOC with OC axial wall heights of two, three, and four millimeters demonstrated significantly greater load to failure as compared to preparations containing zero and one OC axial wall height. The calculation of failure stress was inconclusive and deserves further analysis. Failure mode

analysis suggests, even with the use of adhesive technology, an axial wall height of four millimeters may be required for optimal retention in molar preparations containing 16 degree TOC.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Tooth preparation for successful fixed prosthodontic restorations has traditionally-established parameters that include degrees of taper, minimal preparation reduction recommendations, as well as features that provide proper retention and resistance form with the overall goal of conserving tooth structure.[1] These guidelines were formulated in the era of non-adhesive, aqueous-based luting cements, which largely provided the restoration with macro-mechanical retention by filling the space between the intaglio restoration surface and the prepared tooth surface.[2] However, with the advent of all-ceramic restorations, adhesively-bonded resin cements are utilized more to provide both micromechanical features as well as chemically adhering the restoration to the preparation.[3] Advocates of digital dentistry techniques suggest that adhesion can counterweigh the effect of less than optimal preparation retentive and resistance features.[4,5,6,7]

Finish lines and occlusal convergence are two preparation elements over which the clinician usually has significant control. It is recommended to have an occlusal-cervical (OC) to facial-lingual (FL) ratio of 0.4 in order to prevent the tipping movement of a crown.[8] With this ratio, a 4 mm OC molar preparation height has been traditionally recommended for adequate retention and long term stability.[1] This recommended height, however, is not always achievable and preparations could be less than ideal as crown lengthening may not be a financial, esthetic, or functional option. A restorative treatment option which can surmount these challenges would provide practioners with more clinical options. It has been asserted the total occlusal convergence should be between two to six degrees. However, studies have shown that practitioners cannot usually maintain this taper and the average convergence ranges between 14 and 27 degrees.[9-11]

Some proponents of computer aided design and computer aided manufacturing (CAD/CAM) dentistry anecdotally claim that adhesive bonding cements can compensate for less than ideal preparation features and allow full coverage restoration treatment options that would traditionally require elective endodontic treatment or periodontal surgical procedures. The purpose of this study was to determine if adhesive bonding procedures may compensate for reduced OC axial wall height with full coverage preparations based on a moderate (16 degree) total occlusal convergence (TOC). Furthermore, another objective of this study was to evaluate if failure stress calculations could be more discriminative than the traditional failure load reporting of restoration retention. The null hypothesis was that there would be no difference in the failure stress and load between preparations of 0, 1, 2, 3, 4mm axial wall preparation height.

METHODS

Sixty freshly-extracted human maxillary molar teeth were collected from local oral and maxillofacial surgery clinics which had been removed as per routine clinical indications under the 81rst Medical Group Institutional Review Board (IRB) protocol approval.

The teeth were randomly assigned to five groups (n = 12) and the occlusal surfaces removed to one millimeter below the marginal ridge with a slow-speed, water cooled diamond saw (Buehler, Lake Bluff, IL, USA). The sectioned teeth were then mounted in autopolymerizing denture base methacrylate resin (Diamond D, Keystone Industries, Cherry Hill, NJ, USA). All ceramic crown preparations were accomplished by one operator following recommended guidelines (CEREC 3D Preparation Guidelines, Sirona Dental Systems, Charlotte, NC, USA) for CAD/CAM restorations, including rounded shoulder margins and rounded internal line angles, using a high-speed electric dental handpiece (EA-51LT, Adec Newburg, OR, USA) with a diamond

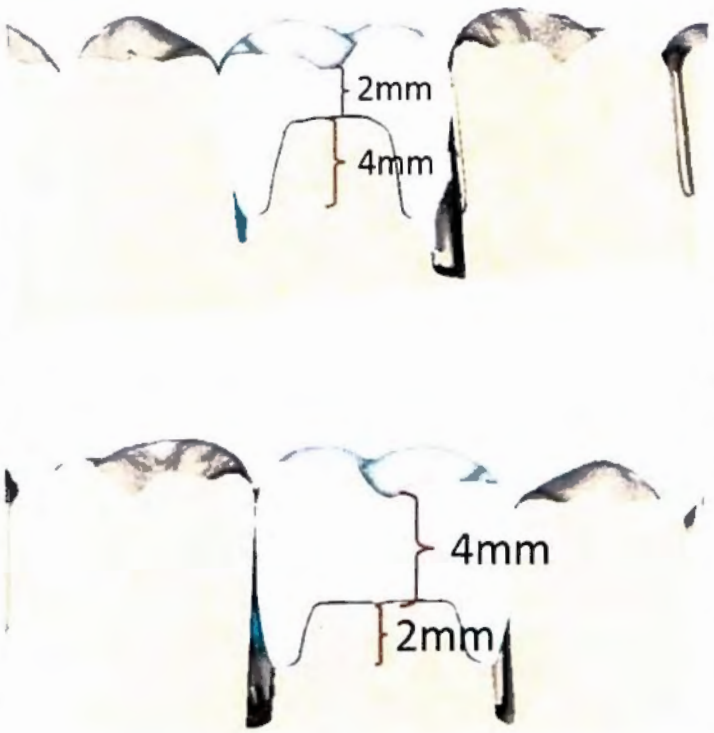
bur (8845KR.31.025, Brassler USA, Savannah, GA, USA) under continuous water coolant spray. Preparations contained finish lines established approximately one millimeter above the cervical enamel junction with the desired axial wall height produced within each group by occlusal reduction of dentin exposed from the initial occlusal sectioning. Preparation taper (16 degrees) was standardized with the handpiece placed in a fixed lathe arrangement.

Each group contained crown preparations containing OC axial wall heights with either zero, one, two, three, or four millimeters. To facilitate correct placement of the restorations, the group with zero OC axial wall heights were additionally prepared with a facial-lingual groove the approximate width and half-depth of a #8 round bur placed. This groove was placed in the same approximate vector of the planned loading force for a negligible impediment to dislodging forces. All final preparations were reviewed and margins refined by a board-certified prosthodontist. Preparation parameters (exposed dentin area, OC axial wall height, and TOC) were then determined and confirmed with a digital measuring microscope (KH-4400, Hirox USA, Hackensack, NJ, USA).

The prepared tooth specimens were restored by one operator using a CAD/CAM acquisition device (CEREC® AC/CEREC MC XL, Sirona Dental Systems, Charlotte, NC, USA, Software version 4.2.4.72301) according to manufacturer instructions and/or recommendations. All specimens were scanned using a standardized template to simulate clinical conditions. The occlusal table was replicated for all specimens and was used to maintain the same restoration height containing a minimum occlusal thickness of 2mm (Figure 1). The design of each restoration was then completed to ensure proper contours and adequate restoration thickness following manufacturer and/or material recommendations (CEREC® 3D Preparation Guidelines, Sirona Dental Systems, Charlotte, NC, USA). The restorations were milled from a lithium disilicate

ceramic restorative material (e.max® CAD, Ivoclar-Vivadent, Amherst, NY, USA). Upon milling, two coats of glaze (IPS e.max® CAD Crystall/Glaze spray, Ivoclar-Vivadent) were applied to the restorations and were crystallized following manufacturer protocol in a dental laboratory ceramic furnace (Programat P700, Ivoclar-Vivadent).

Figure 1. 2mm Occlusal Thickness For 4mm OC Preparation; 4mm Occlusal Thickness For 2mm OC Preparation



The milled restorations were adjusted and seated for each prepared tooth using a disclosing agent (Occlude®, Pascal International, Bellevue, WA, USA) after which the restoration's intaglio surface was steam cleaned and dried. Intaglio surfaces were then prepared with a 5%

hydrofluoric acid etch (IPS® Ceramic Etching Gel, Ivoclar-Vivadent) for 20 seconds, rinsed with water spray, and dried with oil-free compressed air. A coat of silane agent was applied to the etched ceramic surface (Monobond™ Plus, Ivoclar-Vivadent) using a microbrush following manufacturer instructions. After 60 seconds of reaction time, the silane agent was air-dried using oil-free compressed air.

Prepared tooth surfaces were prepared for cementation by cleaning with a pumice and water slurry, rinsed, and dried using oil-free compressed air. A self-adhesive resin cement (Rely-X™ Unicem, 3M ESPE, St. Paul, MN, USA) was placed into the intaglio surface of the ceramic restoration and seated using digital finger pressure of approximately two pounds of seating pressure verified by a calibrated weight. Excess cement from the margin was removed with a rubber tipped gingival stimulator (GUM® latex free stimulator Sunstar Americas, Inc.), with the restoration then exposed to a light emitting diode (LED) visible light curing unit (VLC) for 20 seconds on all surfaces (Bluphase G2, Ivoclar-Vivadent). The completed specimens were stored under dark conditions at 37 ± 1 °C and 98 ± 1% humidity.

Twenty four hours after cementation each specimen was placed into a vise fixture on a universal testing machine (RT-5, MTS Corporation, Eden Prairie, MN, USA) with the long axis of the tooth at a 45-degree angle to the testing fixture (Figure 2).

Figure 2. Sample Testing Configuration

The palatal cusp was loaded with a three millimeter diameter hardened, stainless steel piston with a 0.5 millimeter radius of curvature as described by Kelly *et al.*[12] Specimens were loaded at a rate of 0.5 millimeter per minute until failure with the failure load recorded in Newtons with the resultant failure stress calculated based on measured preparation surface area. Failure mode for each specimen was determined by visual examination under 20X magnification (KH-4400, Hirox USA) to determine if the failure was cohesive for the lithium disilicate ceramic, adhesive failure between the ceramic and the tooth structure, catastrophic failure of the tooth/restoration complex, or cohesive fracture of the tooth material apical to the preparation. Failed specimens were also evaluated using microtomography (MicroCT) (Skyscan 1172, Bruker MicroCT, Kontich, Belgium) at a resolution of 9.8 microns using 100kV energy with a 0.4-degree step size. Individual images were combined into a 3D image using recombination software (nRecon, Bruker MicroCT) and analyzed with a volume-rendering 3D software (CTVox, Bruker MicroCT).

The Shaprio-Wilk Test and Bartlett's Test ascertained normal distribution of the data and homogenous variance. An analysis of variance (ANOVA) and Tukey's *post hoc* test was then performed using a computer-based program (SPSS 20, IBM SPSS, Chicago, IL, USA) with a 95 percent level of confidence ($p = 0.05$).

RESULTS

Table 1. Mean Failure Loads (N) and Stress (MPa)

Axial Wall Height	Failure Load (N)	Failure Stress (MPa)
0 mm	567.6 (200.3) A	6.66 (2.4) A
1 mm	601.9 (281.7) A	6.17 (2.6) A
2 mm	930.8 (357) B	7.81 (2.4) A
3 mm	963.5 (333.3) B	6.99 (7.1) A
4 mm	1034.8 (259.5) B	6.12 (6.1) A

(n = 12) Groups identified with same capital letter are similar within each column (ANOVA; Tukey, p = 0.05)

Failure load and stress results are listed in Table 1. Failure load identified that the preparations with two, three, and four millimeters of ferrule demonstrated significantly greater resistance to failure than the preparations with one and zero ferrule. However, the calculated failure stress results found all of the groups were statistically similar.

Table 2. Failure Mode Analysis

Axial Wall Height	Failure Mode			
	Adhesive Crown Debond	Catastrophic Fracture Tooth/Restoration Complex	Cohesive Root Fracture	Cohesive Ceramic Fracture
0 mm	9	1	0	2
1 mm	10	0	1	1
2 mm	9	0	3	0
3 mm	9	0	1	2
4 mm	0	3	7	2

n = 12

Failure mode results are presented in Table 2. Under the conditions of this study, a non-restorable fracture that involved the tooth and restoration preparation was deemed as a catastrophic failure. On the other hand, a cohesive fracture was one that was apical to and not involving the tooth/restoration complex. Hence, a cohesive root fracture identified that the cohesive strength of the root dentin was less than that of the adhesively-luted restoration. The majority of the preparations with zero millimeter OC axial wall height preparations failed adhesively, one suffered a catastrophic tooth fracture and two displayed cohesive ceramic fractures. The preparations containing one millimeter OC axial wall height group demonstrated predominately adhesive failures as well, but had one cohesive root fracture as well as one cohesive ceramic failure. The preparations containing two and three millimeter OC axial wall height groups were largely similar to the previous groups, with minor differences in root and cohesive ceramic fractures. However, the preparations with four millimeters of OC axial wall height group experienced no adhesive failures and largely failed due to cohesive root fracture followed by catastrophic tooth failure.

DISCUSSION

Retention and resistance form of full coverage indirect restorations are determined by a combination of preparation taper, surface area, and axial wall height.[1,8,9,13] Goodacre *et al* recommended a minimum of four millimeters of OC axial wall height within a recommended 10 to 20 degrees TOC for the full-coverage, indirect restoration of molars.[8,9] Goodacre also proposed an ideal ratio of the OC dimension to the FL dimension to be 0.4 or greater to prevent the tipping motion of a restoration.[8] In the case of molars this ratio of 0.4 is achieved with an OC axial wall length of at least 4mm. Accordingly, with traditional metal substructure crowns the addition of secondary factors, such as boxes and grooves, may compensate in providing additional retention and resistance features with preparations containing less than ideal TOC and OC axial wall height. [1,8,9,13] Of interesting note, a study in 1991 by Parker et al found only 46% of molars have the required ratio of 0.4 or greater, [8,14] while studies by Tiu et al [10,11] reported that 236 preparations submitted to a commercial dental laboratory contained a TOC range from 23 to 78 percent.

With the advent of CAD/CAM technology, preparation designs now differ significantly from traditional tooth preparation recommendations as features may be more limited due to milling unit constraints and milling bur diameters. Anecdotally, proponents of CAD/CAM dentistry advocate that adhesive technology compensates for traditional preparation features which were required in the era of aqueous-based luting cements, and could allow more clinical options when facing the restoration of teeth with compromised tooth structure due to disease and/or parafunction.

This study evaluated if the adhesive bonding procedures involved with all-ceramic CAD/CAM restorations could compensate for reduced molar OC axial wall height with preparations containing a moderate TOC of 16 degrees. Specimens were prepared in a standardization lathe device using a high-speed handpiece with water cooling spray similar to the clinical situation. The prepared tooth features were evaluated and measured at 20x magnification using a digital recording microscope which allowed the determination of surface area (Figures 3 and 4) as well as confirmation of TOC convergence (Figure 5) and OC axial wall height. Preparation TOC was determined by taking the mean of convergence measurements involving the facial-lingual and mesio-distal planes.

Figure 3. Surface Area Determination Axial Wall

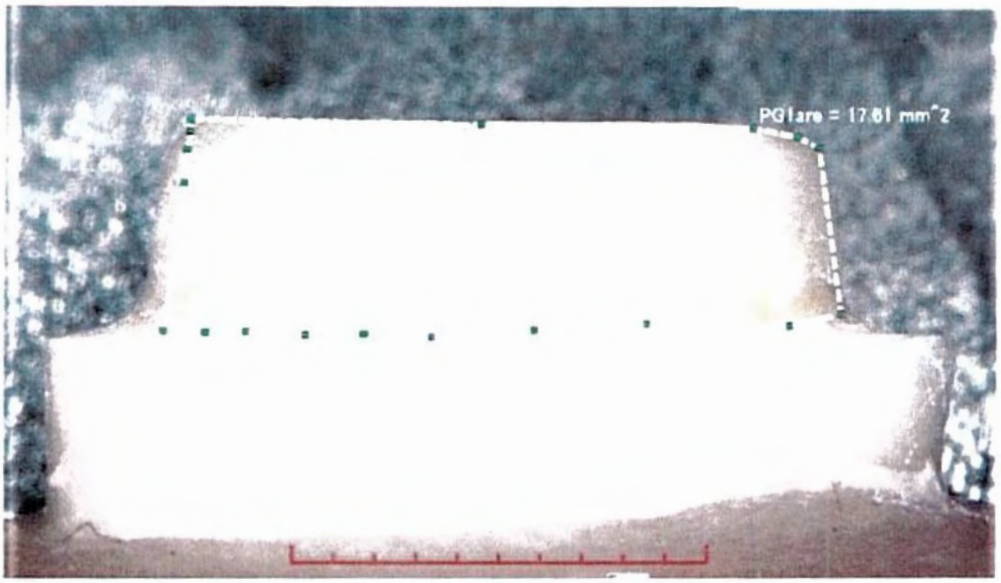


Figure 4. Occlusal Table and Margin Surface Area Determination

Figure 5. Occlusogingival Convergence Determination

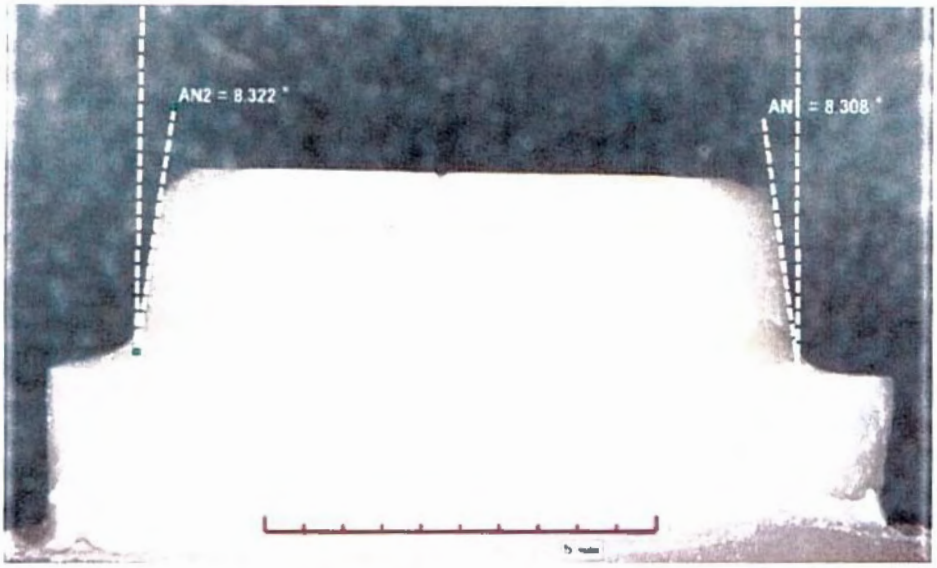


Table 3. Mean Tooth Preparation Parameters

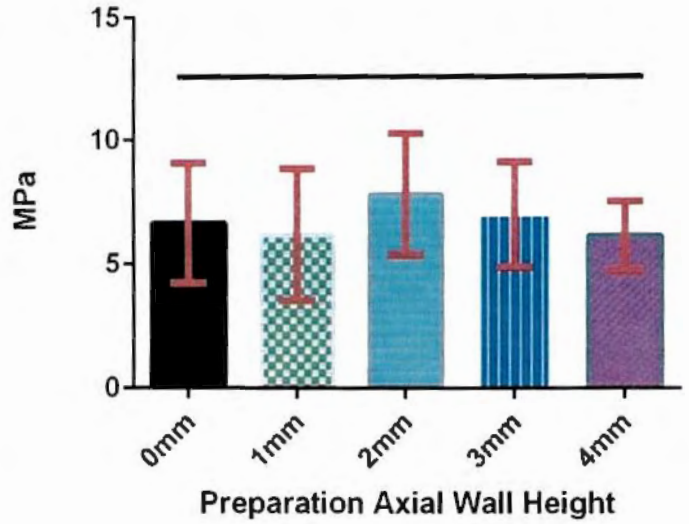
Group Axial Wall Height	Axial Wall Height (mm)	Total Occlusal Convergence (°)	Dentin Surface Area (mm^2)
0 mm			86.8 (17.1)
1 mm	1.05 (0.03)	16.8 (0.5)	95.6 (9.9)
2 mm	2.04 (0.02)	16.5 (0.4)	117.8 (15.1)
3 mm	3.08 (0.04)	16.3 (0.7)	136.5 (12.3)
4 mm	4.04 (0.03)	16.3 (0.3)	169.4 (18.9)

n = 12

The mean measured preparation parameters for the five groups are listed in Table 3. The surface area determination allowed failure stress calculation, which the authors propose may compensate for the inherent difference with traditional failure load due to differences in tooth size.

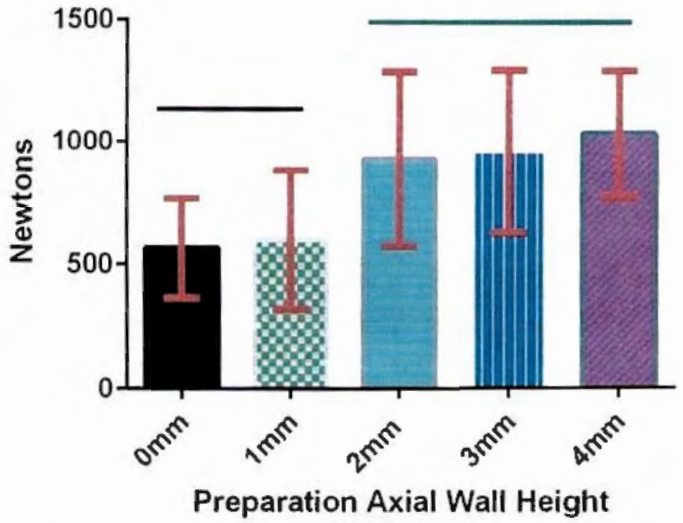
The graphical results of the mean failure stress and failure load are shown in Figures 6 and 7, respectively. The null hypothesis considering failure stress was confirmed but was rejected under the evaluation using failure load. Although the authors propose the failure stress calculation may normalize failure load results, no clear advantage was observed under the conditions of this study. Further studies with increased sample sizes will be required before a definitive determination may be made.

Figure 6. Mean Failure Stress (MPa)



n = 12; Similar groups are connected with same color bar (ANOVA, p = 0.05)

Figure 7. Mean Failure Load (N)



n = 12; Similar groups are connected with same color bar (Tukey, p = 0.05)

The normal occlusal load in the molar region has been reported to be near the range of 100–200 N [15] and has been estimated as high as 965 N in situations of accidental occlusal biting and/or trauma.[15-21] Accordingly, a fracture resistance greater than 1000 N has been recommended for good clinical performance.[22] The results of this study should be mediated with the knowledge that all groups in this study failed at loads higher than that reported for the normal range, with the groups containing two through four millimeters ferrule failing at loads reported for parafunction.[22]

The results of the failure mode analysis offers potentially more clinical implications than failure load or stress. Failure modes were defined as cohesive ceramic fracture when the lithium disilicate ceramic was the sole failure point, adhesive crown debond when the failure was between the ceramic and the tooth structure, root fracture when there was a cohesive tooth material fracture apical to and not involving the preparation, and finally catastrophic failure as when there was a non-restorable fracture of the tooth and restoration complex. Some confusion may exist as to why a root fracture is not classified as a catastrophic failure. Under the conditions of this study, a catastrophic failure represented a non-restorable fracture that involved both the preparation feature and the adhesively-luted restoration. Philosophically, the catastrophic failure partially represents the results of the preparation and restoration effect on the tooth. On the other hand, a root fracture apical to and not involving the tooth/restoration process represents a cohesive failure of the root dentin before the adhesively-luted restoration failed. Hence, the cohesive strength of the root dentin was less than the strength of the adhesively luted restoration. While all the samples had similar failure stress, preparations containing four millimeters of axial wall height samples demonstrated the highest failure load that was accompanied with a high number of cohesive root fractures. In comparison, the groups with lesser preparation ferrule features predominantly failed adhesively. This failure

mode analysis suggests that with molar preparations containing a moderate 16 degree TOC that a four millimeter axial wall height would represent the best retentive outcome, even with the use of adhesive luting agents.

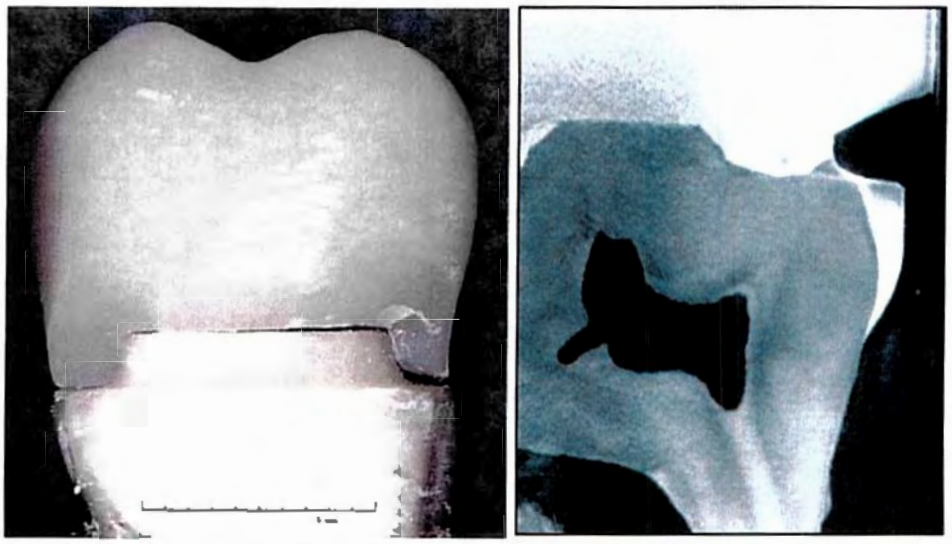
This study simulated the clinical situation of reduced OC axial wall height preparation features that contained a stable restorative occlusal table height. Accordingly, this situation mandated an increase in occlusal surface thickness as the OC axial wall height decreased. Thus, if the occlusal thickness of the lithium disilicate material was considered to be a determining factor of ceramic cohesive fracture, it would be anticipated that the three and four millimeter OC axial wall height groups might present increased cohesive ceramic failures. However, this was not demonstrated by the failure mode analysis and may relate to lithium disilicate strength as well as possible interactions with the self-adhesive resin cement used in this study.

Figure 8. Microscopic and MicroCT Images of Catastrophic Failure in a Zero Millimeter Sample

The majority of the preparations with zero millimeter OC axial wall height failed adhesively between the ceramic crown and the tooth material. Surprisingly, this group did contain one cohesive ceramic fracture and one catastrophic failure, which may demonstrate the bonding strength of the adhesive cement, at least in some instances (Figure 8).

For the one millimeter OC axial wall height group, ten of the twelve specimens failed adhesively with the remaining two samples failing by either cohesive ceramic fracture or cohesive root fracture (Figure 9). The cohesive ceramic fracture occurred in the cervical buccal surface, opposite from the palatally applied force, which could be due to a sharper occlusal/axial wall convergence that perhaps intensified internal ceramic material internal stresses.

Figure 9. Ceramic Fracture Microscopic and MicroCT Slice Images



The number of adhesive failures remained similar throughout all the groups with the exception of the four millimeter OC axial wall height groups, which demonstrated more catastrophic fractures and cohesive root fractures, of which MicroCT examples are illustrated in Figures 10-11.

Figure 10. Four Millimeter Axial Wall Height Catastrophic Failure

Moreover, seven of the twelve of the four millimeter OC axial wall height group demonstrated experienced root fracture, which suggests that the adhesive/ceramic strength of the restoration was greater than the cohesive strength of the root dentin. In these cases, the true strength of the tooth/restoration complex could not be definitively determined, as the tooth root failed before failure of the restoration. This may account for the numerically lower failure stress values observed with the four millimeter OC axial wall height group.

Figure 11. Four Millimeter Group Root Fracture

This study evaluated preparations containing a moderate TOC of 16 degrees that was within the recommended parameters as set forth by Goodacre *et al.*[9] It is reasonable to propose, based on the failure mode of this study, that even with intervention with adhesive technology, molar preparations containing a 16 degree TOC require four millimeters of OC axial wall height for optimal retention.

This study's findings may provide some clinical insight in regards to full-coverage restorations using adhesive technology. The chief limitation is in regards to the restoration failure loads experienced in this study as compared to occlusal load range reported by human function. This evaluation using fatigue methods would augment the results of this study.

CONCLUSIONS

Under the conditions of this study, molar preparations containing a 16 degree TOC with OC axial wall heights of two, three, and four millimeters demonstrated significantly greater load to failure as compared to preparations containing zero and one OC axial wall height. The calculation of failure stress was inconclusive and deserves further analysis. With adhesively luted, all ceramic full coverate restortation, failure mode analysis suggests that an axial wall height of four millimeters may be required for optimal retention in molar preparations containing 16 degree TOC.

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