UNIFORMED SERVICES UNIVERSITY OF THE HEALTH SCIENCES
AIR FORCE POSTGRADUATE DENTAL SCHOOL
301 Fisher Street, Room 1F505
Keesler Air Force Base, Mississippi 39534
www.usuhs.mil

21 June 2018

The author hereby certifies that the use of any copyrighted material in the thesis manuscript entitled:

Effect of 30⁰ Taper on Molar CAD/CAM Crown Retention

is appropriately acknowledged and beyond brief excerpts, is with the permission of the copyright owner.

[redacted]

Signature

Dr. Terrell M. Mitchell

Printed Name

AEGD 24 Month Residency Program
Air Force Postgraduate Dental School
Uniformed Services University of the Health Sciences

Effect of 30° Taper on Molar CAD/CAM Crown Retention

Maj (Dr.) Terrell M. Mitchell, USAF, DC

APPROVED:

[redacted]

Lt Col John A. Brewster (Chairman)
Director, Keesler AFB Postgraduate Dental Research

[redacted] for Dr. Roberts

Colonel (Ret) Howard W. Roberts
Former Director, Keesler AFB Postgraduate Dental Research

21 June 2018

Date

APPROVED:

[redacted]

Colonel Jay D. Graver
Dean, Air Force Postgraduate Dental School

Effect of 30° Taper on Molar CAD/CAM Crown Retention

Terrell M. Mitchell

ABSTRACT

Objective: Evaluate the effect of molar 30° total occlusal convergence (TOC), at varying axial wall heights (AWH), on retention of adhesively bonded lithium disilicate CAD/CAM crowns.

Methods: Sixty recently extracted third molars were divided into 5 groups (n=12). Each group received standardized 30° TOC all-ceramic crown preparations. Groups consisted of preparations with AWH 0-4mm. The surface area, mean AWH, and mean TOC for each preparation was determined using a digital measuring microscope (KH-7700, Hirox USA). The preparations were scanned (Sirona CEREC Omnicam AC/ CEREC MC XL), fitted with milled lithium disilicate crowns (IPS e.max CAD) and cemented with a dual cure self-adhesive resin cement (RelyX Unicem 2) following HF acid etching and silanation. All manufacturer recommendations were followed. Specimens were stored at 37C/98% humidity for 24 hours and then tested to failure at a 45° angle on a universal testing machine. Failure load was recorded in Newtons (N) and failure stress calculated in megapascals (MPa) using the available bonding surface area with mean data analyzed using Kruskal-Wallis/Dunn's post hoc test (p=0.05).

Results: With regards to mean failure load, 2-4mm AWH preparations were statistically similar. Although failure stress was calculated, the research and clinical relevance of these values has yet to be determined.

Conclusions: Within the limitations of this study, when preparing molar teeth for milled lithium disilicate crowns to be bonded with dual cure self-adhesive resin cement, an abutment height as minimal as 2mm provides adequate resistance form. However, total occlusal convergence appears to be more critical than abutment height.

INTRODUCTION

Even in early dental literature, tooth preparation was thought to be a critical factor in the clinical success of single unit crowns. In his sixth edition text, published in 1920, George Evans writes, “Bicuspids and molars with or without pulps, for all-gold crowns, should have as much of the natural crown left as possible, as it affords a more secure and more convenient attachment for the artificial crown than any other method.” [1] Evans was referring to the principle we know today as “preservation of tooth structure.” [18] But the Evans text, like many others around its time, was based on clinical experience, coming prior to the emergence of the evidence based practice and the use of scientific research to further our understanding of how tooth preparation effects crown retention.

It would take another thirty to forty years before prosthodontic preparation guidelines would progress from a foundation in clinical experience to a basis in scientific studies.[2] Two keys principles emerged from these early studies; retention and resistance form. Retention form is defined as, “the feature of a tooth preparation that resists dislodgment of a crown in a vertical direction or along the path of placement” and resistance form is defined as, “the features of a tooth preparation that enhance the stability of a restoration and resists dislodgment along an axis other than the path of placement.” [3] For many years, retention form, tested through ultimate tensile failure, was thought to be the more significant principle negating crown dislodgment, and as such, the bulk of the literature centered on it. [4-9] One of the major determinants of retention form was parallelism of opposing preparation walls. As stated by Shillingburg, “the essential element of retention is two opposing vertical surfaces in the same preparation.” [18] That being the case, total occlusal convergence (TOC) emerged as a central preparation feature and paradigm in studying parallelism in research. Early studies recommended 5-12° TOC for maximum tensile retention. [4, 9]

In the late 20th century, it was recognized that crown dislodgment was actually more sensitive to lateral force than tensile force and the principle of resistance form supplanted retention form in importance. [10-12] Consequently, many researchers opted for testing methods that used some form of lateral force application; with TOC remaining a highly important preparation feature. Applying this new methodology, Dodge et al, tested preparations 3.5 mm in occlusocervical (OC) height and 10 mm in diameter with tapers of either 10, 16, or 22° TOC. Their study found 16° to be the optimal TOC permitting adequate resistance form to prevent crown dislodgment. [11] Inadequate resistance was produced at 22°; and, although 10 and 16° showed no statistically significant difference, the researchers felt that 16° coincided with what had been shown to be clinically achievable overall taper by clinicians in other studies, none averaging a minimum less than 12° TOC. [13-17] A more liberal Shillingburg would later recommend any TOC within the 10 and 22° range. [18]

As resistance form emerged as the dominant principle effecting crown retention, features other than TOC were also recognized as critical to optimal resistance form, namely occlusocervical (OC) dimension and the ratio of occlusocervical dimension to faciolingual dimension (OC/FL). For molar preparations, Goodacre concluded, from the available research, the acceptable dimensions for these features to be 4 mm OC dimension and a 0.4 OC/FL dimension ratio. [2] At the time, it was known that prepared molars averaged greater TOC than any other tooth. [17] Thus, it was theorized that at least 4 mm OC dimension was needed to offset the greater average TOC of molars whose overall taper often fell at the far end of the acceptable spectrum. [2]

It is important to note that all the aforementioned guidance was established when luting indirect restorations with aqueous based cements like zinc phosphate, polycarboxylate, and glass ionomer was prevalent. Although some luting agents are capable of forming a chemical bond to tooth structure, with regards to the intaglio surface of the restoration, they offer purely mechanical/frictional retention. Explained best by Shillingburg, "the geometric configuration of the tooth preparation must place the cement in compression to provide the necessary retention and resistance." [18] The above changed with the advent of adhesive resin cements because for the first time the potential of a chemical bond to both tooth structure and the intaglio surface of metal and ceramic restorations was possible. This new cementation style has ultimately led to current research exploring if the conventional guidelines for crown preparations were applicable for adhesively bonded indirect restorations.

Crowns fabricated from lithium disilicate offer the potential for the chemical bond mentioned above along with other advantages. Lithium disilicate has superior esthetics to gold and porcelain fused to metal restorations, it has an ease and speed of fabrication never seen before using CAD/CAM technology, and it is one of few ceramic materials capable of standing up to posterior occlusal forces. Although the research into adhesively bonding milled lithium disilicate restorations is constantly growing, few studies have evaluated the effects of reducing both retention and resistance features. Thus, the purpose of this study was to evaluate the effect of molar axial wall height (AWH) on retention of adhesively bonded lithium disilicate CAD/CAM crowns with an excessive 30° TOC. The null hypothesis being, for molar preparations with a 30° TOC, there would be no difference in failure load/stress between 0, 1, 2, 3, and 4mm AWH groups.

MATERIALS AND METHODS

A total of 60 freshly extracted human third molars were obtained under the guidance of the 81st Medical Group Institutional Review Board (IRB) protocol. The teeth were randomly assigned to 5 groups (n=12). Each tooth was mounted in an auto polymerizing methacrylate resin denture base material (Diamond D, Keystone Industries, Cherry Hill, NJ, USA). Each group of specimens received standardized 30° TOC preparations following preparation guidelines established for lithium disilicate CAD/CAM restorations (CEREC 3D Preparation Guidelines, Sirona Dental Systems, Charlotte, NC, USA). Preparations were accomplished by a single operator using diamond burs (8845KR.31.025, Brassler USAA, Savannah, GA, USA) and a high speed electric handpiece (EA-51LT, Adec Newburg, OR, USA) with copious water spray. The handpiece was inserted into a fixed lathe milling device. Finish lines were standardized at a level 1mm above the cervical enamel junction with the overall OC axial wall height being achieved by occlusal reduction. Groups consisted of preparations with axial wall heights of 0, 1, 2, 3, and 4mm. To allow for correct orientation, the zero millimeter AWH group was additionally prepared with a facial-lingual groove using half the depth of a # 8 round bur. The groove was placed parallel to the planned loading force vectors in order to minimally affect dislodging forces. All specimens were examined by board-certified Comprehensive Dentist. The surface area, mean TOC, and mean AWH of the completed preparations was determined using a digital measuring microscope (KH-7700, Hirox USA). Figure 1 shows a Hirox image of a preparation from the 4mm group. Table 1 shows the mean AWH, TOC, and dentin surface area for each study group.

Figure 1: Hirox Scan of a 4mm Preparation

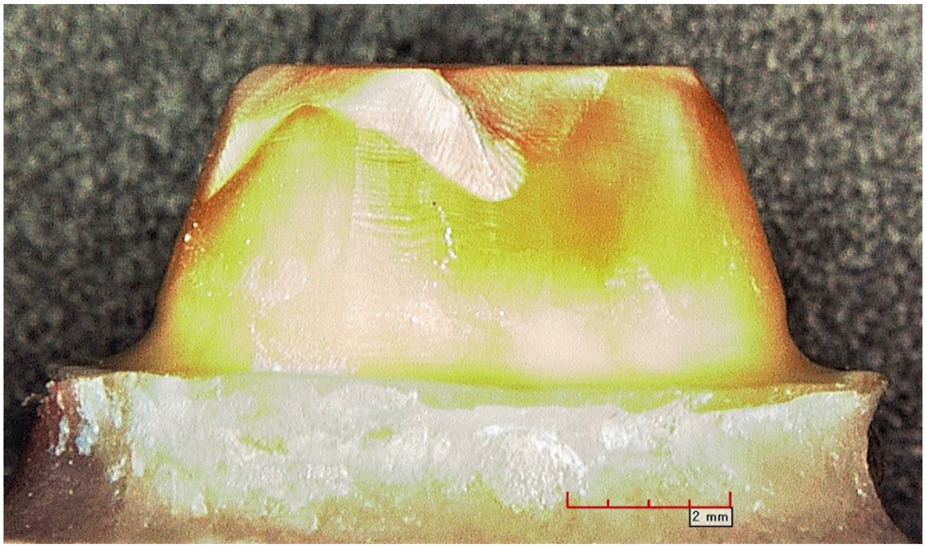


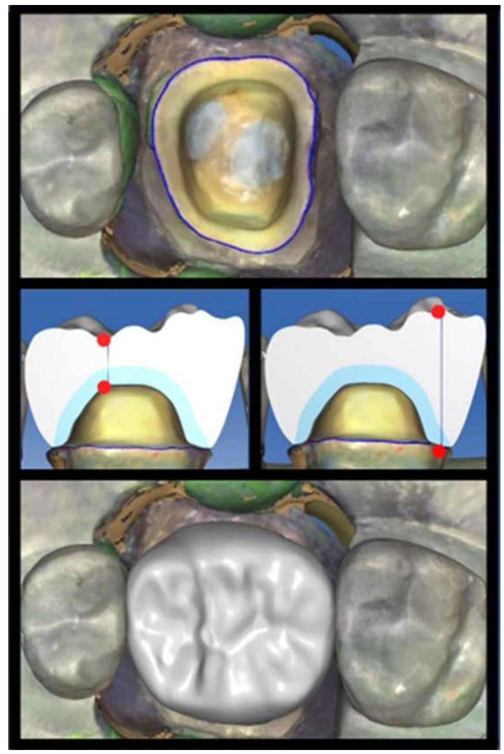
Table 1: Mean AWH, TOC, and Dentin Surface Area

Mean Tooth Preparation Parameters			
Group Axial Wall Height	**Mean Axial Wall Height (mm)**	**Total Occlusal Convergence (°)**	**Dentin Surface Area (mm²)**
0 mm			75.34 (10.7)
1 mm	1.06 (0.05)	30.03 (0.51)	86.36 (10.68)
2 mm	2.03 (0.07)	30.64 (0.42)	102.03 (12.60)
3 mm	3.08 (0.04)	30.65 (0.78)	116.93 (17.30)
4 mm	4.00 (0.03)	30.40 (0.66)	135.99 (14.78)
n=12			

Preparations were digitally captured using a CEREC OmniCam acquisition unit (CEREC AC, Sirona Dental Systems, Charlotte, NC, USA) and crowns were designed using a "Biogeneric Copy" of a standard template (Figure 2 and 3). Restoration features were refined by a single operator with contours, anatomy, and material thickness verified with manufacturer's recommendations. Crowns were milled (CEREC MC XL, Sirona Dental Systems, Charlotte, NC, USA) from size C14 lithium disilicate ceramic blocks (IPS e.max CAD, Ivoclar Vivadent, Amherst, NY, USA), polished pre-crystallization, and crystallized following manufacturer instructions in a dental laboratory ceramic furnace (Programat P700, Ivoclar-Vivadent).

Figure 2: Scanning Template

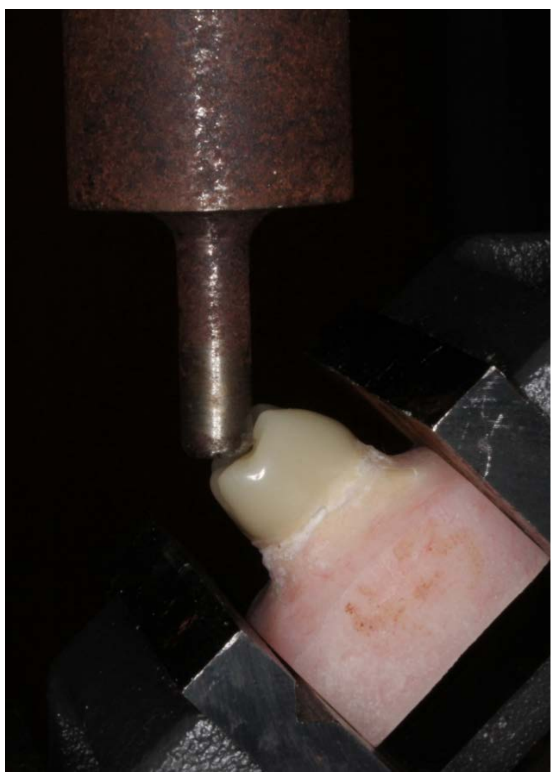
Figure 3: Digital Scan and Design Process (CEREC OmniCam)



The intaglio surface of each restoration was steam cleaned/dried, etched with 5% HF acid (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 seconds, and repeat steam cleaned/dried. The etched ceramic surfaces were then silanated for 60 s (Clearfil Ceramic Primer Plus, Kuraray) following manufacturer's instructions and air-dried. Specimen tooth surfaces were prepared for cementation using pumice/water slurry cleaning followed by rinsing and air drying. Restorations were delivered using a dual-cure self-adhesive resin cement (RelyX Unicem 2, 3M ESPE, St. Paul, MN, USA) placed into the intaglio surface followed by complete seating using digital finger pressure. Excess cement was removed with a microbrush and tack curing accomplished using a light emitting diode (LED) curing light (Bluephase G2, Ivoclar-Vivadent) for approximately 2 seconds on facial and lingual surfaces. Remaining excess cement was then removed and followed by a final cure of 20 seconds completed for the buccal, lingual, and occlusal surfaces to simulate a clinical environment. Specimens were then stored under dark conditions at 37 ± 1 °C and 98 ± 1% relative humidity.

After 24 hours, specimens were placed into a vise fixture on a universal testing machine (Alliance RT-5, MTS Corporation, Eden Prairie, MN, USA). With the long axis of the tooth at a 45° angle to the testing fixture, the facial cusps were loaded with a 3 mm diameter, hardened, stainless steel piston, with a 0.5-meter radius of curvature, at a rate of 0.5 mm/min until failure (Figure 4). The failure load was recorded in Newtons (N) and failure stress calculated in Megapascals (MPa) based on available bonding surface area. Failure mode was determined by visual examination under 20X magnification (KH-7700, Hirox USA). Additionally, failure mode was evaluated using X-ray micro-tomography (Skyscan 1172, Bruker MicroCT) at a 9.24µm resolution, 100kV energy with a 0.4° step size. Individual images were combined into 3D using recombination software (nRecon) and analyzed with volume-rendering 3D software (CTVox). Mean data was first analyzed using Shapiro-Wilk/Bartlett's Test to asses normal distribution and homogeneity of variance. The data was found to be not normally distributed and therefore a non-parametric Kruskal-Wallis/Dunn's post hoc test ($p=0.05$) was utilized at a 95% confidence interval.

Figure 4: Sample Testing Configuration



RESULTS

The results for mean failure load are shown in Table 2 and Figure 5. With regards to mean failure load, 2, 3, and 4mm OC AWH preparations were statistically similar with the 2mm group exhibiting the greatest mean failure. Additionally, the 0 and 3mm groups were statistically similar. The 1mm OC AWH group exhibited the lowest mean failure and this was statistically significant.

Table 2: Mean Failure Load (N)/Stress (MPa) at 30°

Mean Failure Load (N) and Stress (MPa)		
Group AWH	Failure Load (N)	Failure Stress (Mpa)
0 mm	323.6 (136.6)B	4.2 (1.7)A
1 mm	134.9 (67.7)C	4.8 (2.6)A
2 mm	695.3 (164.5)A	6.9 (1.8)B
3 mm	539.3 (240.3)AB	4.6 (2.1)A
4 mm	695.0 (330.1)A	5.1 (2.1)A

Groups with same capital letter are statistically similar within each column. (p=0.05)

The results for mean failure stress are shown in Table 2 and Figure 6. With regards to mean failure stress 0, 1, 3, and 4mm OC AWH preparations were statistically similar. The 2mm group was superior to all other groups and this difference was statistically significant.

Figure 5: Mean Failure Load

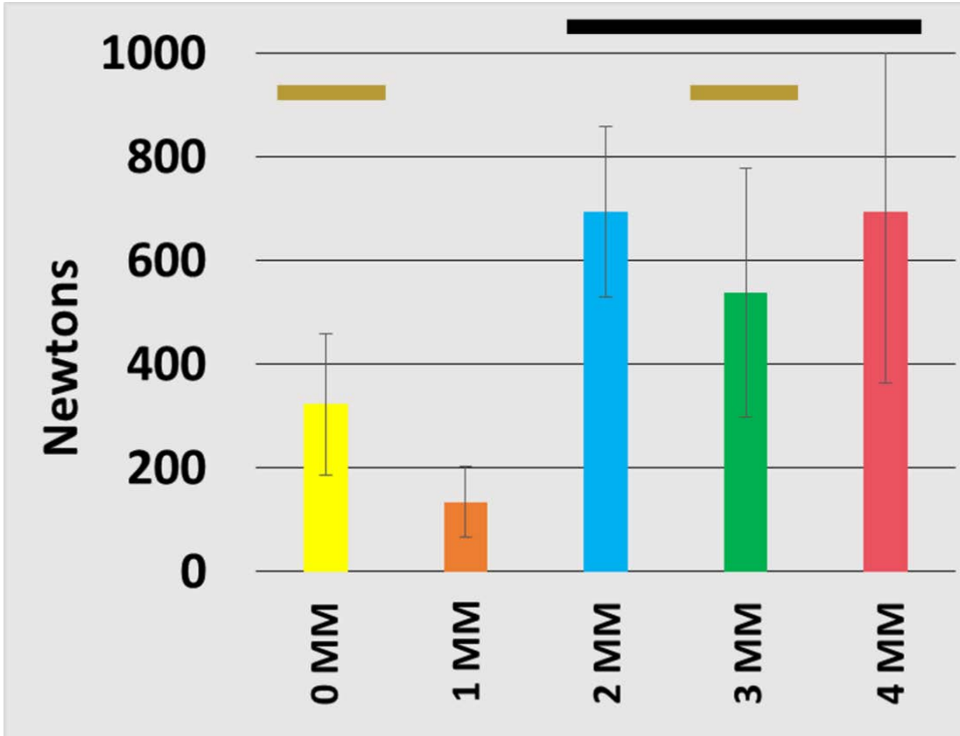
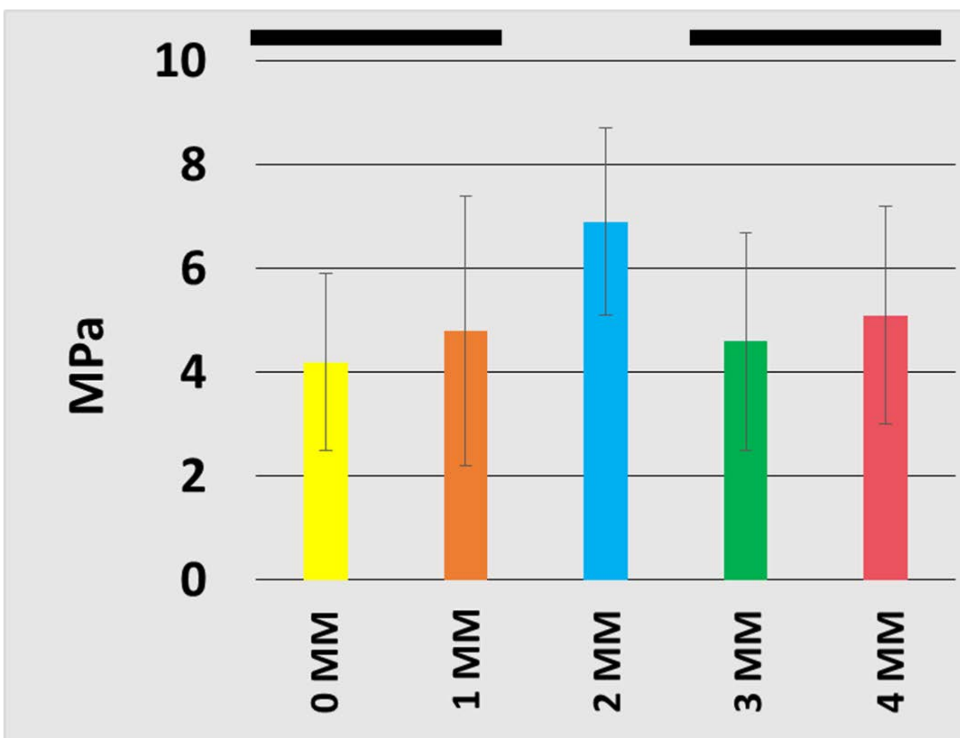


Figure 6: Mean Failure Stress



Failure modes are shown in Table 3. For 0 through 3mm OC AWH preparations mode of failure was predominately adhesive failure. The 4mm group exhibited an equal number of adhesive failures and tooth fractures. A digital photo and Micro CT image of a tooth fracture from the 4mm group are shown in figures 7 and 8 respectively.

Table 3: Failure Modes

Failure Mode Analysis			
Group AWL	**Adhesive Failure**	**Tooth Fracture**	**Cohesive Ceramic Failure/Fracture**
0 mm	12	0	0
1 mm	9	1	0
2 mm	11	1	0
3 mm	10 (1 TF)	2 (1 AF) (1 CF)	2 (1 TF)
4 mm	5	5	0

Parentheses denotes more than one failure mode

Figure 7: Photo of 4mm Tooth Fracture

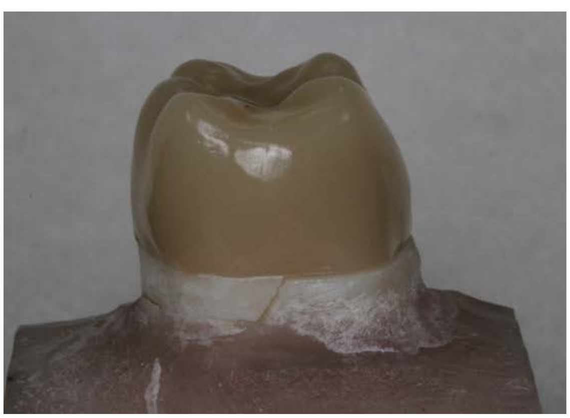


Figure 8: Micro CT Image of 4mm Tooth Fracture

DISCUSSION

Conventional guidelines for molar crown preparations state that a maximum of 22° TOC, a minimum of 4 mm OC AWH, and a minimum 0.4 OC/FL dimension ratio are required for adequate resistance form. [2, 18] The purpose of this study was to determine if adhesively bonding CAD/CAM ceramic restorations could compensate for molar preps with a combined reduced OC AWH with 30° TOC. This study chose to standardized taper; thus, AWH was the selected preparation feature for comparative analysis. The null hypothesis that there would be no difference in failure load/stress between 0, 1, 2, 3, and 4mm AWH groups was rejected as all groups did not perform statistically similar. With the exception of the 2 mm group which was statistically superior, all groups exhibited statistically similar failure stress; although failure stress values were calculated, the research and clinical relevance of these values has yet to be determined. Conversely, it is worth noting that there was no statistically significant difference between the 2, 3, and 4mm AWH groups in terms of failure load. Thus, within the limitations of this study, 2 and 3mm AWH preparations have resistance form as favorable as 4mm AWH preparations despite excessive 30° TOC.

The current study is the last in a compendium that also analyzed the effect of molar AWH at standardized tapers of 10, 16, and 20° TOC. Those studies exhibited acceptable molar TOC based on the available research.[18] Furthermore, they support the findings of the current research, also exhibiting the trend of no statistically significant difference in the 2, 3, and 4mm AWH groups in terms of failure load. The collated results of the four studies suggest that bonding lithium disilicate crowns (IPS e.max CAD) with dual cure self-adhesive resin cement (RelyX Unicem 2) can compensate for some reduction in AWH relative to a standardized taper. The results of these studies are shown in Tables 4-6.

Tables 4, 5, 6: Mean Failure Loads (N) at 10, 16, 20°

10° TOC	
Axial Wall Height	**Failure Load (N)**
0 mm	291.1 (124.0) A
1 mm	735.1 (310.9) B
2 mm	1170.0 (297.6) C
3 mm	1253.4 (210.0) C
4 mm	996.2 (424.1) BC

16° TOC	
Axial Wall Height	**Failure Load (N)**
0 mm	567.6 (200.3) A
1 mm	601.9 (281.7) A
2 mm	930.8 (357) B
3 mm	963.5 (333.3) B
4 mm	1034.8 (259.5) B

20° TOC	
Axial Wall Height	**Failure Load (N)**
0 mm	129.5 (97.6) A
1 mm	174.3 (74.0) A
2 mm	474.7 (207.1) B
3 mm	798.8 (371.4) B
4 mm	862.9 (360.0) B

The tables above are from studies conducted by Wake et al (2015), Hoopes et al (2016), and Spriggel et al (2017).

A recent study by Yi-Chen Huang et al lends further support to the aforementioned analysis. [22] Using similar methods, the research group varied AWH (6 groups consisting of 2, 3, and 4mm AWH preparations, either with or without proximal grooves) on molars with standardized overall tapered of 20° TOC. Preparations received cast metal copings bonded with dual cure adhesive resin cement (RelyX Unicem 2). A similar trend of the resin cement compensating for inadequate preparation height was noted, with no statistically significant difference in failure load between the 3 and 4mm AWH groups without proximal grooves. Furthermore, it is worth noting that proximal grooves only made a statistically significant difference within the 4mm AWH groups; they had no effect in the 2 and 3mm AWH preparation. [22]

From these studies, it appears that emerging evidence is beginning to challenge the conventional guidelines for molar crown preparation. Those guidelines should not only be challenged as they pertain to state of the art adhesive resin cements and ceramics, but also on the quality of evidence from which these recommendations were made. Undoubtedly, they were established from the best available evidence of the time, but a critical review of the literature using current standards is warranted. As stated by the GRADE working group, credited with developing a common, sensible, and transparent approach to grading quality of evidence and strength of recommendations in health care research settings, “clinical guidelines are only as good as the evidence and judgments they are based on.” [24]

One example of the above, the minimum 0.4 OC/FL dimension ratio for molar preparations actually has a mathematic foundation based solely in theory, which today would qualify as no more than expert opinion, the lowest level of evidence. This theory was developed by Parker et al, seeking to establish OC/FL dimension ratios and "critical convergence angles" beyond which crown preparations supposedly would not possess adequate resistance form. [20, 21] The only supporting evidence of this theory comes in the form of three studies with serious limitation with regard to quality of study design. [21, 31, 32] Despite the quality of evidence surrounding the principle of critical convergence angles, many others held similar beliefs to the Parker group regarding resistance form as having an all or none nature. Belief in this principle was such that it even effected study design, with many studies applying methods in which failure load testing was conducted on dies with uncemented crowns under the impression that if resistance form was present the crowns would not dislodge. [11, 19, 21, 32] Those studies went on to shape the parameters for TOC and OC preparation height for molars despite serious limitations in study quality and clinical relevance. Furthermore, Parker et al seemingly knew of the lack of clinical relevance of the theory and methods, stating in one study, "Although more than 50% of the preparations lacked resistance form, a high degree of 'failure' was not seen clinically." [21] Ultimately, this points to the need for an unbiased systematic review of the historic literature and modification of principles of preparation as needed, instead of reliance on a summary article, which itself is no more than expert opinion.

Another metric by which to examine the current study data is comparison to human molar bite force. Helkimo et al measured this force in 125 participants, aged 15 to 65, finding mean values of 382 N in males and 216 N in females in the molar region. [29] Conversely, Antti et al measured this force in 30 undergraduate dental students (n=15 per sex), finding mean values of 847 N for males and 597 N for females in the molar region. [28] The studies differ in participants' age and state of their dentitions. Antti studied mostly young, healthy, fully dentate participants; Helkimo studied a more heterogeneous group with regards to age range and state of the dentition, with participants ranging from fully dentate to completely edentulous. Overall, the studies give an approximation of decreasing molar bite force with age and tooth loss. Comparing them to the results of the current study, none of the AWH groups meet the maximum male bite force in Antti et al. However, the 2, 3, and 4mm AWH groups surpass the maximum male bite force in Helkimo et al. Thus, the current study provides experimental failure loads for 0-4mm AWH molar preparations at 30° TOC and lends a general idea of how those groups may hold up against a static molar bite force in patient populations. That being stated, there are limitations to this study with regards to its methods.

First, this study only evaluated static force failures. As previous stated, crown dislodgment has been reported to be more sensitive to lateral force than tensile force. [10-12] However, emerging studies also make it apparent that the manner of this force application is critical [25, 26]. Mastication is a dynamic process with humans averaging 250,000 masticatory cycles per year [27]. The ability of preparation design and cementation style to resist cyclic loading therefore holds significance. As such, including cyclic loading into the methods of future studies should be considered.

Second, this study did not evaluate the durability of adhesive cementation with aging. It is well known that bond strength decreases with aging. As stated by Breschi et al, "despite immediate efficacy, there are major concerns when dentin bonded interfaces are tested after aging even for short time period." [27]   Samples in the study were tested after only 24 hours of storage at 37 ± 1 °C and 98 ± 1% relative humidity. This limited the ability to assess to what degree bond stability would influence retention. As such, aging of samples must be given consideration in future research.

Third, this study used 0 mm AWH preps as a control. A cursory glance draws immediate attention to the seemingly aberrant mean failure load in this group. However, looking to the compendium of research, to include the 10, 16, 20° molar TOC studies, it becomes apparent that the 0 mm groups have high inherent variability, having failed at mean loads ranging from 129.5 (97.6) N to 567.6 (200.3) N (Tables 2 and 4-6). All groups were tested on the same universal testing machine. However, the 0mm preps were flat topped 1mm above the CEJ of each tooth, an area of high variability of the dentin surface dependent on the history of tooth. Futures studies should eliminate this group as it fails to function as a control and holds little clinical relevance.

Finally, one limitation exists beyond the study methods. Failure load was not recorded for 5 samples due to malfunction on the Alliance RT-5 testing machine. With small sample sizes (n=12), the aforementioned sample loss may decrease statistical power and undermine statistical significance; in these situations, groups that appear statistically similar may in fact be different, given adequate sample size and sufficient power.

As a final note, studying progressive taper at a standardized AWH was not an objective this series of studies. However, provided the raw data now exists, the authors would be remised to not take at least a cursory glance at the effect of adhesive bonding on progressive taper. Circa 1950, Jorgensen demonstrated that as convergence angles increased retention decreased. [4] Regarding Tables 2 and 4-6, generally speaking, with the exception of 0mm AWH groups, increased taper lead to decreased failure loads when comparing each preparation AWH group. Thus, Jorgensen's observations seemingly hold true whether luting or bonding single unit restorations; adhesive bonding does not appear to be able to negate the effects of increased preparation taper. It should be noted that this is a cursory observation with no statistical backing. Further research aimed at answering the question of the effect of progressive taper on bonding single unit crowns is warranted.

CONCLUSIONS

Within the limitations of this study:

1) When preparing molar teeth for lithium disilicate ceramics to be bonded with dual cure resin cement

- An abutment height as minimal as 2mm provides adequate resistance form
- Total occlusal convergence appears to be more critical than abutment height

Furthermore, this study highlights a need for further research to include prospective clinical studies and bench top studies with methods to include cyclic fatigue testing and bond aging. Finally, the ability to grade research quality and strength of recommendations now exist. As such, a secondary review of the literature on which conventional principles of tooth preparation are based may be warranted and beneficial.

REFERENCES

1. Evans, George. *A Practical Treatise on Artificial Crown-, Bridge-, and Porcelain-Work*. Henry Kimpton, 1923.

2. Goodacre, C., Campagni, W., Aquilino, S. Tooth preparations for complete crowns: An art form based on scientific principles. J of Prosthet Dent. 2001; 85: 363-76.

3. The Glossary of Prosthodontic Terms. J Prosthet Dent. 2005; 94: 10-92.

4. Jorgensen, K.D. The relationship between retention and convergence angle in cemented veneer crowns. Acta Odontol Scand. 1955; 13:35-40.

5. Shillingburg, H.T., Hobo, S., Whitsett, L.D. *Fundamental of Fixed Prosthodontics*. Chicago, IL: Quintessence Publishing Co; 1981.

6. Dykema R.W., Goodacre C.J., Phillips, R.W. *Johnston's Modern Practice in Fixed Prosthodontics*. 4th ed. Philadelphia, PA: WB Saunders; 1986.

7. Malone, W.P, Koth D.L. *Tylman's Theory and Practice of Fixed Prosthodontics*. 8th ed. St. Louis, MO: Ishiyaku Euro America, Inc; 1989.

8. Rosenstiel S.F., Land M.F., Fujimoto, J. *Contemporary Fixed Prosthodontics*. 2nd ed. St. Louis, MO: Mosby–Year Book; 1995.

9. Wilson A.H., Chan, D.C. The relationship between preparation convergence and retention of extracoronal retainers. J Prosthodont. 1994; 3:74-8.

10. Wiskott, H.A., Nicholls, J.I., Belser, U.C. The relationship between abutment taper and resistance of cemented crowns to dynamic loading. Int J Prosthodont. 1996; 9:117-39.

11. Dodge, W.W., Weed, R.M., Baez, R.J., Buchanan, R.N. The effect of convergence angle on retention and resistance form. Quintessence Int. 1985; 16:191-4.

12. Wiskott, H.W, Nicholls, J.I, Belser, U.C. The effect of tooth preparation height and diameter on the resistance of complete crowns to fatigue loading. Int J Prosthodont. 1997;10:207-15

13. Nordlander, J., Weir, D., Stoffer, W., Ochi, S. The taper of clinical preparations for fixed prosthodontics. J Prosthet Dent. 1988;60:148-51.

14. Leempoel, P.B, Lemmens, P.L, Snoek, P.A., van't Hof, M.A. The convergence angle of tooth preparations for complete crowns. J Prosthet Dent. 1987; 58:414-6.

15. Mack, P.J. A theoretical and clinical investigation into the taper achieved on crown and inlay preparations. J Oral Rehabil. 1980; 7:255-65.

16. Eames, W.B, O'Neal, S.J, Monteiro, J., Miller, C., Roan, J.D., Cohen, K.S. Techniques to improve the seating of castings. J Am Dent Assoc. 1978; 96:432-7.

17. Kent, W.A, Shillingburg, H.T., Duncanson, M.G. Taper of clinical preparations for cast restorations. Quintessence Int. 1988; 19:339-45.

18. Shillingburg, H.T., Hobo, S., Whitsett, L.D., Jacobi, R., Brackett, S.E. *Fundamentals of Fixed Prosthodontics*. 3rd ed. Chicago, IL: Quintessence Publishing Co; 1997.

19. Woolsey, G.D., Matich, J.A. The effect of axial grooves on the resistance form of cast restorations. J Am Dent Assoc. 1978; 97:978-80.

20. Parker, M.H., Calverley, M.J., Gardner, F.M., Gunderson, R.B. New guidelines for preparation taper. J Prosthodont 1993; 2:61-6.

21. Parker, M.H., Malone, K.H., Trier, A.C., Striano, T.S. Evaluation of resistance form for prepared teeth. J Prosthet Dent. 1991; 66:730-3.

22. Huang, Y., Lin, C., Wen-Ching Ko, E. Effects of proximal grooves and abutment height on the resistance of resin-cemented crowns in teeth with inadequate resistance: an in vitro study. Biomed J. 2015; 38:336-341

24. GRADE Working Group. Grading quality of evidence and strength of recommendations. BMJ : British Medical Journal. 2004; 328(7454):1490.

25. Attia, A., Kern, M. Influence of cyclic loading and luting agents on the fracture load of two all-ceramic crown systems. J Prosthet Dent 2004; 92:551-6.

26. Attia, A., Kern, M. Fracture strength of all-ceramic crowns luted using two bonding methods. J Prosthet Dent 2004; 91:247-52.

27. Att, W., Kurun, S., Gerds, T., Strub, J.R. Fracture resistance of single-tooth implant-supported all-ceramic restorations: an in vitro study. J Prosthet Dent. 2006; 95:111-6

28. Waltimo, A. and Könönen, M. A novel bite force recorder and maximal isometric bite force values for healthy young adults. European Journal of Oral Sciences. 1993; 101: 171-175.

29-Helkimo, E., Carlsson, G. E. and Carmeli, Y. Bite force in patients with functional disturbances of the masticatory system. Journal of Oral Rehabilitation. 1975; 2: 397-406.

30-Breschi, L., Mazzoni, A., Ruggeri, A., Cadenaro, M., Lenarda, R., De Stefano Dorigo, E. Dental Adhesion Review: aging and stability of the bonded interface. Dental Materials: official publication of the Academy of Dental Materials. 2008; 24. 90-101.

31-Trier, A.C., Parker, M.H., Cameron, S.M., Brousseau, J.S. Evaluation of resistance form of dislodged crowns and retainers. J Prosthet Dent; 80:405-9.

32-Weed, R.M., Baez, R.J. A method for determining adequate resistance form of complete cast crown preparations. J Prosthet Dent 1984; 52:330-4.