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Fracture Load of Zirconia Crowns Based on Preparation and Cement Type

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Abstract

Limited research has been published evaluating the failure of cubic zirconia crowns with non-retentive preparations. **Objective:** The purpose of this study was to evaluate the effect of axial wall height (AWH) and cement type on the fracture load of cubic zirconia crowns. **Methods:** Ninety extracted maxillary human third molar teeth were prepared with standardized crown preparations with AWHs of zero, two, or four millimeters (n=10). The preparations were scanned and crown restorations were designed (Omnicam, Dentsply/Sirona). Cubic zirconia crowns (4Y-TZP, Katana STML, Kuraray) were milled (MCXL, Dentply/Sirona) and cemented with either a RMGI (RelyX Luting Plus, 3M/ESPE), a self-adhesive resin (RelyX Unicem, 3M/ESPE), or an adhesive resin cement (Panavia V5, Kuraray). The specimens were stored for 24 hrs in 37°C distilled water, then subjected to thermocycling and cyclic loading. Each crown specimen was loaded to failure in a universal testing machine (Instron) at a 60-degree angle to the long axis of the tooth using a stainless-steel rod resting on the buccal incline of the palatal cusp. Data were analyzed with Kruskal-Wallis and Mann-Whitney U tests (alpha=0.05). **Results:** Significant differences in fracture load were found between groups based on AWH and cement type ($p<0.05$). **Conclusions:** Regardless of cement type, the mean fracture loads were significantly lower for the zero millimeter AWHs than with 2 millimeter or 4 millimeter AWHs, which were not significantly different from each other. Compared to the other cement types, the adhesive resin cement provided a significantly greater fracture load with the zero millimeter AWH.

Introduction

Metal-ceramic prosthesis have been a less favorable alternative in dentistry due to aesthetic needs, and zirconia has occupied a more important role due to mechanical and biocompatible characteristics [1]. McLaren divided dental ceramics into 4 groups determined by the material composition. Category 1 materials are glass-based systems that contain mainly silica dioxide and varying amounts of alumina. Category 2 are also glass-based systems that contain silica as well as crystalline fillers such as flourapatite, leucite, and lithium disilicate correlating to increased flexural strength and fracture toughness retaining a high translucency. Category 3 materials are crystalline-based systems with glass fillers resulting in high flexural strength. Lastly, Category 4 consists of polycrystalline solids of alumina or zirconia oxides with no glass matrix resulting in high strength but less translucency [2]. Categories 1 and 2 are traditionally etched with hydrofluoric acid, silanated, and bonded with resin based cements to maximize adhesion and strength [3]. However due to their intrinsic strength, Categories 3 and 4 do not require adhesive cementation unless retention is compromised [4].

In its pure form, zirconia can exhibit three phases; monoclinic, tetragonal, and cubic. While the stability of these phases is dependent on increasing temperature, it is possible to achieve each phase at room temperature by adding stabilizing oxides [5]. The most widely used form of zirconia for dental applications is in the tetragonal phase which is a high temperature phase stabilized by adding 3 mol% yttrium oxide (Y_2O_3) and therefore know as 3% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) [5]. Y_2O_3 is added to purified zirconia powder to stabilize the tetragonal phase and prevent it from transforming to the weaker monoclinic phase [6]. New formulations of zirconia were developed by increasing the amount of Y_2O_3 to improve translucency and increase cubic phase content [6]. In these new zirconia materials, the quantity of the cubic phase increases from very low levels in 3Y-TZP materials to approximately 25 vol% in 4Y-TZP materials and up to 50 vol% in 5Y-TZP materials [6].

One of the unique properties of zirconia is increased ability to resist fracture also known as transformation toughening. As the zirconia transforms from its metastable tetragonal phase to the monoclinic phase due to externally applied stresses, it exhibits a decrease to fracture by expansion and shape change within individual grains absorbing energy and affording damage resistance [6, 7]. The highest fracture toughness is exhibited in 3Y-TZPs and the lowest in 5Y-TZPs. Less transformation toughening is exhibited in translucent 4Y and 5Y zirconia due to their reduced possibility of transformation from tetragonal to monoclinic [6].

While the strength of zirconia is a desirable feature, the material presents a challenge when trying to obtain an adhesive bond with non-retentive preparations. Zirconia does not contain glass particles like glass-ceramic materials and therefore cannot be etched with hydrofluoric acid and bonded with silane to the intaglio surface [6]. Therefore, it may require additional surface treatment (air abrasion) and unique surface primers.

Conservative guideline parameters have been established in regards to tooth structure for indirect full-coverage tooth preparations that include degrees of taper, minimal preparation reduction recommendations, and features to enhance proper retention and resistance form [8]. These guidelines were established before the use of adhesive-resin cements and primers and focused on macromechanical retention in which the luting cement occupies the space between the restoration intaglio surface and the prepared tooth [9]. Adhesive resin cements provide some micromechanical properties but also offer the advantage of chemically adhering the restoration to the preparation [10]. Resin cements provide more advantages than luting cements such as optical characteristics similar to natural dentition, improved mechanical properties to strengthen the final restoration, and ability to bond to multiple substrates [11]. With recent research, methacryloyloxydecyl dihydrogen phosphate (MDP) has been shown to chemically interact with mineral oxides and create a strong bond [12]. Traditional zirconia crowns, air abraded with aluminum oxide and treated with primers or cements containing MDP, have shown to have higher bond strengths than non-treated zirconia crowns [13].

Resin-bonding protocols for silica-based ceramics are universally known and accepted. However, most practitioners are still unsure about proper bonding techniques and materials for zirconia [14]. Unlike glassy ceramics, zirconia is resistant to mechanical and chemical surface treatments [1]. There are no clinical long-term studies on the use of zirconia restorations with preparations that contain minimal retentive and resistance features [14]. A reliable adhesion to zirconia materials has yet to be definitively defined, and this study may show that bonding to zirconia may be less predictable with less retentive preparations [1].

To provide adequate resistance form and prevent crown tipping, a 0.4 ratio of preparation AWH to preparation buccal-lingual width is recommended [15]. To achieve this ratio, a four millimeter occlusal-cervical AWH preparation has been suggested with molars [15]. Due to many circumstances, this crown height may not be clinically achievable. Along with this ratio, a total occlusal convergence (TOC) has been advocated to be between two and six degrees [8, 16]. However, studies report that clinicians most often do not meet these parameters with their single-unit preparations. The majority of teeth prepared for zirconia crown preparations achieve a mean TOC of twenty-six degrees clinically [17]. And upon further evaluation, a TOC between ten and twenty degrees is considered adequate for preparation convergence [18]. Dental adhesives and resin cements may be able to compensate for the lack of achieving these ideal goals [19].

A recent study by Hoopes et al evaluated the effects of AWH on the retention of CAD/CAM lithium-disilicate crowns. They discovered that AWHs greater than two millimeters demonstrated similar and higher resistance to fracture than the one and zero millimeter AWH groups [20]. However, there are no published studies evaluating the effect of reduced AWH on the retention of zirconia crowns. The aim of this study was to evaluate if adhesive bonding procedures could compensate for a reduced occlusal-cervical AWH with full coverage preparations based on a moderate (16 degree) TOC to 4Y-TZP cubic zirconia crowns. The null hypothesis was that there would be no difference in the fracture load of cubic-containing zirconia crowns to tooth preparations based on AWH (4, 2, and 0 mm) and type of cement (resin-modified glass ionomer, self-adhesive resin, or adhesive resin cements).

Materials and Methods

Ninety extracted maxillary human third molar teeth were collected and stored in 0.5% chloramine-T solution. The occlusal surfaces of the teeth were removed to one millimeter below the marginal ridge with a high speed, wheel diamond bur (35003.31.039, Brassler USA, Savannah, GA). The sectioned teeth were then mounted in bisacryl (Integrity Temporary Material, Dentsply Sirona Dental Systems, Charlotte, NC). All zirconia crown preparations were accomplished by one operator following the manufacturer recommended guidelines for KATANA STML (4Y-TZP) zirconia material (KATANA Zirconia Preparation Guidelines, Kuraray Noritake Dental, Tokyo, Japan) using a high-speed electric dental handpiece (EA-51LT, Adec, Newburg, OR) with a diamond bur (8845KR.31.025, Brassler USA) under continuous water spray. Preparation TOC (16 degrees) was standardized with the handpiece placed in a vacuum base grip (BVVB Vacuum Base Vice, Bessey, Cambridge, Ontario) and finish lines were established approximately one millimeter above the cervical enamel junction. To establish similar finish lines, all specimens were first prepared with a four millimeter AWH with the margin located within enamel. The desired AWHs of zero, two, and four millimeters were then produced for each group of 30 specimens each by occlusal reduction of dentin exposed from the initial occlusal sectioning (Figure 1). To facilitate correct restoration placement, the zero millimeter AWH group specimens were additionally prepared with a facial-lingual groove the approximate width and half depth of a #2 round bur. This feature was placed in the same approximate vector of the planned loading force to serve as a negligible impediment to dislodging forces.

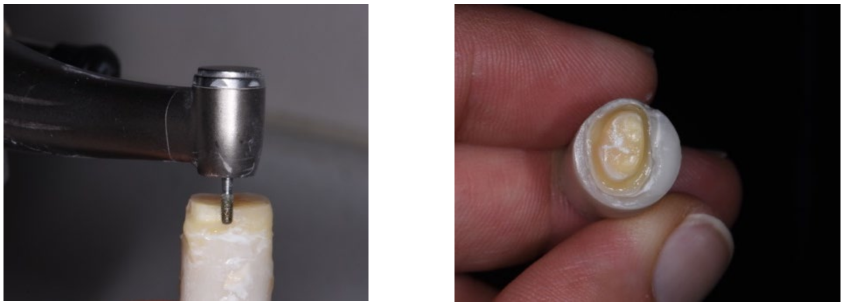

Figure 1: Images demonstrating crown preparation on extracted human third molar

The prepared tooth specimens were restored by one operator using a CAD/CAM acquisition device (CEREC Omnicam/CEREC MC XL, Software version 4.2.4.72301. Dentsply Sirona Dental Systems) according to the manufacturer's recommendations. Prior to scanning, specimens were placed into a standardized template to simulate clinical conditions. Restoration design featured a standardized occlusal anatomy and table height with a minimum occlusal thickness anatomy of 1 mm. The design of each restoration was then completed to ensure proper contours following manufacturer and/or material recommendations with occlusal anatomy standardized using the biocopy feature. Specimens were then milled from a zirconia ceramic restorative material (Shade A2, STML, KATANA, Kuraray). After milling, the restorations were sintered following the manufacturer's instructions in a dental laboratory ceramic furnace (Programat S1 1600, Ivoclar Vivadent, Amherst, NY)

The milled restorations were adjusted and seated for each prepared tooth using a disclosing agent (Occlude, Pascal International, Bellevue, WA) after which the restoration was steam cleaned and dried. Intaglio surfaces were abraded (Basic Quatro IS, Renfert, Chicago, IL) with 50μm aluminum oxide at 2.0 bar at a distance of 10 millimeters, steam cleaned, and dried with 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.

Ten specimens from each of the three AWH groups were cemented with resin-modified glass ionomer, self-adhesive resin, or adhesive resin cements (Table 1). For the resin-modified glass ionomer cement group, RelyX Luting Plus (3M ESPE, St. Paul, MN) was used according to manufacturer's instructions. A small pea sized amount was dispensed through an auto-mixing tube. A thin layer of luting cement was evenly placed in the intaglio surface of the dental protheses. The restoration was seated with digital finger pressure and standardized as much as possible using one researcher. Excess marginal cement was removed with a dental explorer after a 2 minute set time.

Name	**Lot Number**	**Composition**	**Manufacturer**
RelyX Luting Plus	NC02781	Silane treated ceramic, 2-hydroxyethyl methacrylate, Copolymer of acrylic and itaconic acids, water, Glycerol 1,3 dimethacrylate, Potassium disphosphate, Potassium perfulfate, ditertbutyl-4-methylphenol, Ethylene Dimethacrylate	3M ESPE, St. Paul, MN
RelyX Unicem	6716136	Methacrylated phosphoric acid esters, triethylene glycol dimethacrylate, substituted dimethacrylate, silanized glass powder, silane treated silica, sodium persulfate, substituted pyrimidine, calcium hydroxide	
Ceramic Primer Plus	7R0046	3-Trimethoxysilypropyl methacrylate, Methacryloyloxydecyl dihydrogen phosphate, Ethanol	Kuraray Noritake Dental, Kurashiki, Japan
Panavia V5 Tooth Primer	810067	Methacryloyloxydecyl dihydrogen phosphate , 2-hydroxyethyl methacrylate, hydrophobic aliphatic dimethacrylate, accelerators, water	

Panavia V5	7S0027	Bisphenol A-glycidyl methacrylate, Triethylene glycol dimethacrylate, Hydrophobic aromatic dimethacrylate, hydrophilic aliphatic dimethacrylate, Initiators, Accelerators, Silanated barium glass filler, Silanated fluroaluminosilicate glass filler, Colloidal silica, Silanated aluminium oxide filler, dl Camphorquinone, Pigments	

Table 1: Components of cements and primers utilized in this study

For the self-adhesive resin cement group, RelyX Unicem (3M ESPE) was used according to manufacturer's instructions. Cement was then placed in the intaglio surface of the restoration through the auto-mixing tube. The restoration was seated with digital finger pressure and standardized as much as possible as before. A tack cure was applied for two seconds on all surfaces using a light-emitting diode visible-light curing unit (Bluephase G2, Ivoclar Vivadent). Excess marginal cement was removed with an explorer as before. All surfaces were light cured again using the LED visible light curing unit for 20 seconds.

For the adhesive-resin cement group, the dual-cure adhesive cement, Panavia V5 (Kuraray) was used according to manufacturer's instructions. Ceramic Primer Plus (Kuraray) was added to the intaglio surface of the prosthesis. Tooth Primer (Kuraray) was applied to tooth surface, left for 20 seconds, and air dried. The cement was applied to the intaglio surface of the crown and seated with digital finger pressure, standardized as much as possible using one researcher. As before, the excess resin was partially light cured with a light-emitting diode visible-light curing unit for two seconds. Excess marginal cement was removed with an explorer as before. All margin surfaces were cured again using the LED visible light curing unit for 20 seconds.

The crown specimens were placed in distilled water and stored at 37 degrees Celsius for 24 hours in a laboratory oven (Model 20 GC, Quincy Labs, Chicago, IL). The specimens were thermocycled in distilled water for 2000 cycles at 5 + 55°C with a dwell time of 30 seconds at each temperature (Sabri Dental Enterprise, Downers Grove, IL). All teeth were loaded into a cyclic loader (Sabri Dental Enterprises) to simulate chewing function. The machine subjected the mounted teeth, still submerged in distilled water, to a cycling force of 10-150 N at a rate of 1 cycle per second (1 Hz) for 100,000 cycles. The force was applied parallel to the occlusal surface via a 12.7 mm diameter, flat-ended cylindrical piston resting on the cusp tips. Each group (consisting of 10 teeth) were loaded separately from the other groups. The load was verified with a digital force meter (Infinity CS, Cooper Instruments, Warrenton, VA) before each load sequence.

Each specimen was mounted in a PVC pipe at a 30-degree angle from the horizontal with denture acrylic (Vitacrylic, Fricke Dental, Streamwood, IL). Then, each specimen was placed into a vise fixture on a universal testing machine (5943, Instron, Norwood, MA) with the long axis of the tooth at a 60 degree angle to the testing fixture. The buccal incline of the palatal cusp was loaded with a three-millimeter diameter hardened, stainless-steel rod with a 0.5 millimeter radius of curvature. Specimens were loaded at a rate of 1.0 millimeter per minute until failure with the fracture load recorded in Newtons. A median fracture load and interquartile range (IQR) was determined for each group. The Shapiro-Wilk and Bartletts Test was used to ascertain the distribution of the data and homogeneity of the variance, respectively. Due to the non-normal distribution, data were analyzed with Kruskal-Wallis and Mann-Whitney U tests using a statistical software program (SPSS 20, IBM SPSS, Chicago, IL) with a 95% level of confidence ($P= 0.05$). Failure mode for each specimen was determined by visual examination to determine if the failure was due to cyclic loading, adhesive failure between the ceramic and the tooth structure, catastrophic failure of the tooth/restoration complex, cohesive fracture of the tooth material apical to the preparation or cohesive fracture of ceramic.

Results

Significant differences in fracture load were demonstrated between groups based on AWH and cement type (Table 2). Analyzing the data with Kruskal-Wallis and Mann-Whitney U tests, there were significant differences in fracture load based on AWH of the tooth preparations regardless of cement type ($p<0.05$). The fracture load for the zero-millimeter AWH groups were significantly lower than both the two- and four-millimeter AWH groups. There was not a significant difference in fracture load noted in cement type among the two- and the four-millimeter AWH groups. Among the zero-millimeter AWH groups, there was a statistically significant difference in fracture load between the three cement types with the resin-modified glass ionomer and self-adhesive resin cements resulting in significantly lower fracture load than the adhesive resin cement.

AWH	**Fracture Load (Newtons)** Median (IQR)		
	RMGI	Self-adhesive Resin	Adhesive Resin
0 mm	134.6 (306.5) Aa	0.0 (43.2) Aa	702.1 (536.8) Ba
2 mm	1162.4 (910.7) Ab	1524.2 (899.2) Ab	1506.2 (675.3) Ab
4 mm	1566.7 (360.8) Ab	1957.1 (1069.) Ab	1334.3 (883.1) Ab
Groups with the same upper-case letter by row and lower-case letter by column are not significantly different P>0.05			

Table 2: Fracture load in Newtons of Zirconia crowns with various AWHs and cement types.

Failure modes were assessed based on type of failure. Cyclic loading failure was noted in almost half (4/10) of the zero-millimeter AWH resin-modified glass ionomer group as well as a majority (8/10) of the zero-millimeter AWH self-adhesive resin group. Specimens that failed during cyclic loading prior to static loading were assigned a zero fracture load in Newtons. The majority of the adhesive crown debondings were noted in the zero-millimeter AWH groups. The primary failure mode that was consistent among two- and four-millimeter AWH groups and all cement types was the cohesive root fracture.

Cement Type	AWH	**Failure Mode**				
		Cyclic Loading Failure	Adhesive Crown Debonding	Tooth/Restoration Complex Fracture	Cohesive Root Fracture	Cohesive Ceramic Fracture
RMGI	0	4	6	0	0	0
	2	0	0	0	10	0
	4	0	0	2	8	0
Self-Adhesive	0	8	2	0	0	0
	2	0	1	1	8	0
	4	0	0	2	8	0
Adhesive Resin	0	1	5	0	3	1
	2	0	2	0	8	0
	4	0	0	0	10	0

Table 3: Various failure modes based on AWH and cement type

Discussion

The first null hypothesis that there will be no difference in the fracture load of cubic-containing zirconia crowns to tooth preparations based on AWH was rejected. The fracture load was significantly greater for the two- and four-millimeter AWHs compared to the zero-millimeter AWH regardless of cement type. According to Goodacre, the desired AWH with molars is four millimeters. With the decrease in AWH, we anticipated a decrease in the resistance form and therefore a decrease in fracture resistance [15]. This was observed in this study with the minimal fracture resistance numbers seen in the zero-millimeter AWH groups and thus being significantly less than the other groups. The two- and four-millimeter AWH groups were observed to be similar in fracture load. The resin-modified glass ionomer cement group had a lower median fracture load in the two-millimeter compared to the four-millimeter AWH group, but it did not prove to be statistically significant. The lack of variability with the fracture load between the two- and four-millimeter AWH groups could be related to the failure mode of the specimens. Most of the specimens in the two- and four-millimeter AWH groups exhibited catastrophic fracture where the tooth fractured rather than the prosthesis. Therefore, the data reflected the cohesive strength of the tooth rather than the prosthesis itself.

The second null hypothesis that there will be no difference in the failure load of cubic-containing zirconia crowns based on cement type was also rejected. Among the zero-millimeter AWH groups, the adhesive resin cement group demonstrated significantly stronger fracture load compared to the resin-modified glass ionomer and self-adhesive resin cement groups. A previous study showed a trend to yield higher bond strengths to zirconia with adhesive resin cements compared to luting cements such as conventional glass ionomers and resin-modified glass ionomers [21]. This was characteristically seen in this study. However, most of the specimens in the self-adhesive resin cement group with zero-millimeter AWH failed in the cyclic loading stage due to debonding. A recent systematic review of laboratory studies by Miotti et al. showed higher bond strengths of resin cements that utilized adhesive bonding agents compared to the more simplified self-adhesive resin cements. The higher bond strengths may be due to the ability of bonding agents to envelope exposed collagen fibrils to prevent degradation mechanisms. The efficacy of the adhesion may be directly dependent on the priming steps, wetting characteristics of the bonding agent, and its chemical composition, [22]. This was also seen in the data collected in this study at zero-millimeter AWHs. Other studies have shown higher bond strengths to zirconia using cements utilizing 10-methacryloyloxy-decyl dihydrogen phosphate (10-MDP) when compared to cements without 10-MDP [23]. While this was not shown in this research study across the two- and four-millimeter AWH groups, it could have contributed to the success for the adhesive resin cement group in the zero-millimeter axial wall height groups. The separate self-etching tooth primer containing 10-MDP used with Panavia V5 could have resulted in greater fracture resistance when compared to the resin-modified glass ionomer and self-adhesive resin cements.

The methods utilized in this study were similar to a previous study conducted by Hoopes et al. In that study, the authors evaluated the effect of various AWHs and a self-adhesive resin cement on the fracture resistance of lithium-disilicate glass-ceramic crowns. Similar to that study, most adhesive crown debondings were noted in the smaller AWH groups, primarily the zero-millimeter AWH groups. As the AWH increased in that study, the number of cohesive root fractures increased similar to this study [20]. However, this study exhibited a greater number of cohesive root fractures and and a higher fracture load based on AWH. The increased fracture load is most likely due to the cohesive strength of cubic-containing zirconia compared to natural tooth structure and lithium disilicate [6].

There are no other studies currently comparing the fracture resistance of new cubic-containing zirconia crowns with different types of cement and various AWHs. This study also evaluated the fracture loads of crowns utilizing extracted teeth and not printed dies composed of polymer, which may provide greater clinical validity. Possible shortcomings in this study were the types of failures. Most failures were catastrophic where the tooth fractured instead of the restoration. Therefore, the true fracture resistance of the cement compared to the AWH was not actually measured.

Conclusion

Significantly greater fracture loads and catastrophic root fractures were demonstrated with zirconia crowns with AWHs of 2 millimeters or greater, regardless of cement type. The use of an adhesive resin cement may provide greater fracture resistance with preparations having minimal (zero millimeter) AWH.

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