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Title of Thesis: Effect of Axial Wall Height and Total Occlusal Convergence of 3Y-TZP Zirconia Implant Abutments on the Retention of Adhesively Bonded 3Y-TZP Zirconia Crowns

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Effect of Axial Wall Height and Total Occlusal Convergence of 3Y-TZP Zirconia Implant Abutments on the Retention of Adhesively Bonded 3Y-TZP Zirconia Crowns

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ABSTRACT

Statement of Problem: Currently, no published data exists to provide clinical guidance on decisions relative to total occlusal convergence (TOC) and axial wall height (AWH) regarding a 3Y-TZP zirconia crown bonded to a zirconia abutment.

Purpose: The purpose of this study was to quantify the effect of total occlusal convergence and axial wall height on the resistance form of a milled 3Y-TZP zirconia crown adhesively bonded to a milled 3Y-TZP zirconia custom implant abutment.

Materials and Methods: Eight groups of ten 3Y-TZP zirconia (Sagemax NexxZR T, Washington, U.S.A) crown and 3Y-TZP zirconia abutment (Sagemax NexxZR S, Washington, U.S.A) pairs (n=10) were fabricated. Each group differed in AWH (H-4mm, H-3mm, H-2mm, H-1mm) and TOC (C-7°, C-15°) of the abutment and corresponding crown. 3Y-TZP zirconia crowns and abutments were air abraded with aluminum oxide (50 microns, 20-30psi, steam-cleaned) and adhesively bonded to each other using the Panavia V5 (Kuraray North America, Houston, TX) resin cement system. After cementation, samples were artificially aged with thermocycling (500 cycles, 5-55°C, dwelling time 30 seconds), mounted into the Instron Universal Testing Machine (Instron, Norwood, MA) and forces directed at 45° to the long axis of the sample were applied to failure (debonding or fracture). The mode of failure and the load at which failure occurred was recorded.

Results: 98.75% (79/80) of crowns debonded from their respective abutments and 1.25% (1/80) of crowns fractured. The fractured samples were from the C-7° group with 4mm AWH. Statistically significant difference of load at failure between C-15° group was found within the H-1mm and H-3/H-4 groups.

Conclusions: Results of this *in vitro* study indicate that, when bonded with resin cement, milled 3Y-TZP zirconia crowns will dislodge from milled 3Y-TZP zirconia implant abutments due to lack of conventional resistance form in regard of AWH or TOC. At least 3mm AWH and a maximum of 15° TOC are required to resist crown debonding within the average maximum biting forces.

CLINICAL IMPLICATIONS

When using a split file technique to fabricate 3Y-TZP zirconia single-unit implant-supported restorations, an AWH of 3mm with $\leq$15° TOC will resist dislodging forces when the crown and abutment were bonded with resin cement system.

INTRODUCTION

Endosseous implants were once a novel treatment modality, but that is no longer the case. Today they are a common treatment option. In fact, often times patients present to dental practices around the world with the chief concern "I want an implant". The reality is these patients are missing a tooth or teeth and want them to be replaced in some manner. There are many treatment options for edentulous areas such as a removable partial denture, fixed partial denture, leaving the area edentulous, or an implant retained crown/prosthesis. Each treatment has its own advantages and disadvantages depending on the patient's individual clinical presentation and overall health.

Single unit implant crowns can be restored by means of an implant-supported or an abutment-supported restoration (Shillingburg et al., 2012). An implant-supported restoration is commonly referred to as a "screw-retained implant crown". This mode of treatment involves a full contoured crown attached to the implant directly by means of a screw. An abutment-supported restoration is commonly known as a "cement-retained implant crown". This treatment is achieved by attaching an abutment to the implant with a screw and then cementing a full-contoured crown over this abutment (Shillingburg et al., 2012). Each works well in various clinical scenarios.

Implant-supported or screw-retained restorations have several favorable characteristics. The first is ease of retrievability. If a screw comes loose, fractures, or there is a need to remove the restoration for any other reason, access to the screw is readily available. The screw channel can be easily accessed by removing the obturating restorative material from the screw channel and gain access to the screw to remove the restoration. Implant-supported restorations also work well when there is limited interocclusal space. Since the restoration is one monolithic unit, having adequate space for material bulk and strength is less constringent. Another significant advantage is the absence of requiring cement, so the deleterious effects of retained cement to periodontal health are not a concern (Lee, Okayasu, & Wang, 2010; Michalakis, Hirayama, & Garefis, 2003; Shadid & Sadaqa, 2012).

Screw-retained crowns do have some disadvantages. There is a screw access channel exiting through the restoration, which may negatively affect the esthetics; particularly if it exits the crown in a place other than the incisolingual aspect for anterior teeth, or the occlusal aspect for posterior teeth. Also, a grayish hue can sometimes be seen through the restored access channel due to metal components, when present. Additionally, the screw access channel is often exactly where carefully planned occlusal contacts should be. This can lead to loss of stable occlusion on the restoration since there is less control using a restorative material to obturate this hole (Lee et al., 2010; Michalakis et al., 2003; Shadid & Sadaqa, 2012). The process may also be tedious and time-consuming when delivering the prosthesis. It involves repeatedly screwing and unscrewing the restoration as occlusal and interproximal contacts are checked. Implant supported crowns have notable advantages, primarily retrievability.

Cement-retained restorations provide some distinct advantages over the screw-retained restoration. Cement-retained restorations are used primarily for their ease of delivery. Insertion of a cement-retained crown is far less cumbersome of a process than that of screw-retained. The abutment serves to displace the soft tissue and appropriate fit and contacts are then easily evaluated and achieved. Also, cement-retained crowns can be used to restore when implant angulation of placement is not in line with the insertion axis of the restoration or when the screw access hole would compromise esthetics. Lastly, these restorations are cheaper to make and no additional training is required for the lab technician since traditional fabrication techniques can be employed (Lee et al., 2010; Michalakis et al., 2003; Shadid & Sadaqa, 2012).

Cement-retained restorations have one serious draw back; the possibility of leaving cement extruded from the crown-abutment interface in contact with surrounding tissues. Retained cement is a disadvantage of a cement retained implant crown and a factor in peri-implant disease resulting in inflammation and bone loss around the implant. This destruction of periodontal health due to cement can have a severe and rapid onset. Conversely, removal of the cement leads to improved peri-implant health and a significant reduction in the inflammation present (Korsch, Robra, & Walther, 2015; Linkevicius, Puisys, Vindasiute, Linkeviciene, & Apse, 2013; Pauletto, Lahiffe, & Walton, 1999; Staubli, Walter, Schmidt, Weiger, & Zitzmann, 2017). A clinician may feel this won't be a disadvantage for them personally because they have confidence in their ability to remove excess cement. However, removing the excess cement is more difficult than expected especially considering factors such as the subgingival depth of the abutment and accessibility to remove the cement. Upon evaluating implants, Korsch found that after supposedly removing excess cement, some cement remained 60% of the time (Korsch et al., 2015). The lack of retrievability is another disadvantage of cement retained implant crowns. Since the crown is cemented or bonded to an abutment, it is difficult to remove and often requires cutting the crown off the abutment, destroying it in the process.

To help minimize the risk of retained cement, abutments can be custom designed to place the crown-abutment interface at a location that optimizes esthetics while placing it close enough to the gingival margin to make complete cement retrieval predictable (Linkevicius et al., 2013; Linkevicius, Vindasiute, Puisys, & Peciuliene, 2011; Michalakis et al., 2003; Pauletto et al., 1999; Staubli et al., 2017). There are many materials and methods available for the fabrication of custom abutments. Abutments can be made from metal alloys via the lost wax technique or milled from a variety of materials such as titanium, lithium disilicate, lithium silicate, or from zirconia (Shillingburg et al., 2012).

Zirconium dioxide, commonly known as zirconia, is regularly used to fabricate abutments and crowns. Three different crystal configurations for zirconia exist: monoclinic, tetragonal, and cubic. Yttria is commonly added to zirconia in order to help stabilize it in the tetragonal state resulting in Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP). Zirconia is desired as a dental material because it is very strong (flexural strength 900-1200 MPa), has a high compression strength (2000 MPa) and a good fracture toughness (6 $MPa \cdot m^{0.5}$) (Anusavice, Shen, & Rawls, 2013; Denry & Kelly, 2008; Elsayed, Wille, Al-Akhali, & Kern, 2017; Gomes & Montero, 2011). Additionally, it is a very biocompatible material with long-term documentation due to its common use in orthopedics for total hip replacements since the late 1980's. (Denry & Kelly, 2008; Shillingburg et al., 2012). Zirconia is very resistant to corrosion and is a fairly inert material. Another significant advantage of zirconia is its ability to demonstrate a phenomenon known as transformation toughening. This occurs as tensile stresses develop at crack tips, resulting in a transformation from the tetragonal phase to the monoclinic phase. This phase change results in a

3%-5% volume increase, which produce a high localized compressive stress around these crack tips inhibiting the potential for crack propagation. The material is strengthened and the fracture toughness increases. Zirconia can be milled in a green state, a partially sintered state, or a fully sintered state. If milled in a non-fully sintered (green) state the material must be sintered before it is ready for intraoral use. Unfortunately, this requires substantial time and a special sintering oven (Anusavice et al., 2013; Denry & Kelly, 2008). Zirconia has the potential to offer a more esthetic result than titanium or gold abutments, as it is less noticeable near the gingiva. Glauser et al and Canullo completed research exploring the suitability of zirconia as an abutment material. They found there were no abutment fractures and the hard and soft tissues responded well. They concluded that zirconia is a suitable material for an implant abutment (Canullo, 2007; Glauser et al., 2004). Fracture resistance and implant abrasion are improved when a ti-base is inserted into a zirconia abutment as opposed to having the zirconia interact directly with the implant interface (Elsayed et al., 2017).

In order to minimize the chance of dislodgement following cementation of the crown to the abutment, the design of the prosthetic abutment must adhere to principles of resistance form such as adequate axial wall height and proper taper. Principles of resistance form, as have been established with teeth prepared for crowns, dictate that the abutment must have axial walls that are 4mm long for molars and 3mm long for premolars and anterior teeth. Ideally, these walls will also have a total occlusal convergence of 10-20 degrees (Goodacre et al., 2001; Trier et al., 1998; Woolsey & Matich, 1978). If implant abutments do not exhibit these resistance form principles, crowns may not predictably remain luted in place.

Unfortunately, ideal resistance form cannot always be achieved. Misch defines the space from implant platform to occlusal surface of the restoration as crown height space (CHS) (Misch et al., 2005, 2006). Balancing limited CHS, required minimum thickness for a given crown material, and necessary location of the crown-abutment interface can make the establishment of 3-4mm axial walls impossible. When this occurs, the provider is forced to revert to a screw-retained design or risk fabricating a restoration with inadequate resistance form and there a high risk of crown dislodgement. This undesirable quandary leads one to question if resistance form principles could be negated by bonding, instead of luting crowns to abutments.

There are various ways to attach crowns to prepared teeth or implant abutments. Crowns can be cemented (luted) or bonded to their substrate. Cementing is simply binding two objects together by filling the space between them and allowing the cement to harden. Bonding on the other hand, is joining two objects together using an adhesive which creates a linkage between atoms or radicals of a chemical compound ("The Glossary of Prosthodontic Terms: Ninth Edition," 2017). Traditionally, zinc phosphate and other cements have been used to cement or lute restorations in place (Ayad, Rosenstiel, & Woelfel, 1998; Rosenstiel, Land, & Crispin, 1998). However, with the advent of bonding, crowns are being bonded more frequently than before because adhesive resin cements can achieve significantly higher strengths than conventional cements (Ayad, Johnston, & Rosenstiel, 2009; Browning, Nelson, Cibirka, & Myers, 2002).

Since zirconia is a metal oxide, not a glass ceramic, bonding it with resin cements must be approached differently than bonding dental ceramics. In order to bond to zirconia, a phosphate monomer such as 10-methacryloxyloxy-decyl-dihydrogen-phosphate (10-MDP) is needed as well as a resin cement. The phosphate ester group on one end of the 10-MDP molecule will bond to metal oxides while the carboxyl end of the molecule is readily incorporated into the polymerizing resin cement. The 10-MDP monomer thus forms an ionic bond with both the zirconia and the resin (Blatz, Chiche, Holst, & Sadan, 2007; Kern & Wegner, 1998; Nagaoka et al., 2017; Sellers, Powers, & Kiat-Amnuay, 2017). Kern et al. evaluated how the bond between resin composite and zirconia failed when stresses were placed on it. They found that with 10-MDP present, the failure of the resin cements tested were cohesive in nature and not adhesive. Adhesive failures are when the failure occurs at the junction of the substrate and the cement, which would mean the bond was overcome. Conversely, a cohesive failure occurs within the cement, meaning the stresses overcame the strength of the cement itself, not the bond of the cement to the zirconia. Typically, cohesive failures are preferred when talking about bond strength (Kern & Wegner, 1998).

Gillette et al. showed some evidence that adhesion could compensate for less than ideal axial wall height. This study looked at prepared premolars with conservative total occlusal convergence (10 degrees) and various axial wall heights. Lithium disilicate crowns were then bonded and loaded until failure. There was no difference in failure load between the groups with axial wall height of 2 and 3 mm (Gillette et al., 2016). El-Mowafy et al showed that adhesive bonding with resin cement may be able to overcome overly tapered restorations. In this study, more force was required to dislodge crowns from crown preps with 70 degrees of TOC bonded with resin cement than from crown preps with 24 degrees of TOC luted with zinc oxide (El-Mowafy, Fenton, Forrester, & Milenkovic, 1996). This research on tooth supported restorations has suggested that bonding a restoration can overcome less than ideal resistance form.

HYPOTHESIS

Null hypothesis: There is no statistically significant difference in the amount of force required to dislodge 3Y-TZP zirconia crowns bonded to 3Y-TZP zirconia abutments when the AWH of the abutment and the TOC of those axial walls varies.

Alternative hypothesis: The amount of force required to dislodge 3Y-TZP zirconia crowns bonded to 3Y-TZP zirconia abutments differs significantly when the AWH of the abutment and/or the TOC of those axial walls varies.

MATERIALS & METHODS

Sirona InLab 16.1 design software was used to design "coping" type restorations that served as the basis for the design abutments. The designs were exported as digital STL files that were sent to a milling center (Imagine Milling, Chantilly, VA) for production. The study consisted of eight test groups. These eight groups resulted from the combination of four AWH-groups and two different degrees of TOC. Abutments were designed with a shoulder margin with 1.5 mm axial depth. The designed AWH were 4 mm, 3 mm, 2 mm, and 1 mm and the designed TOC variations were 7 degrees and 15 degrees [Figures 1 & 2]. Abutments were fabricated from 3Y-TZP zirconia (Sagemax NexxZr S, Washington, U.S.A.). The groups consisted of 10 samples each (N=10). Each custom abutment sample was designed with a 20mm extension base apical to the finish line of the abutment. This extension was utilized for fixation in the testing device.

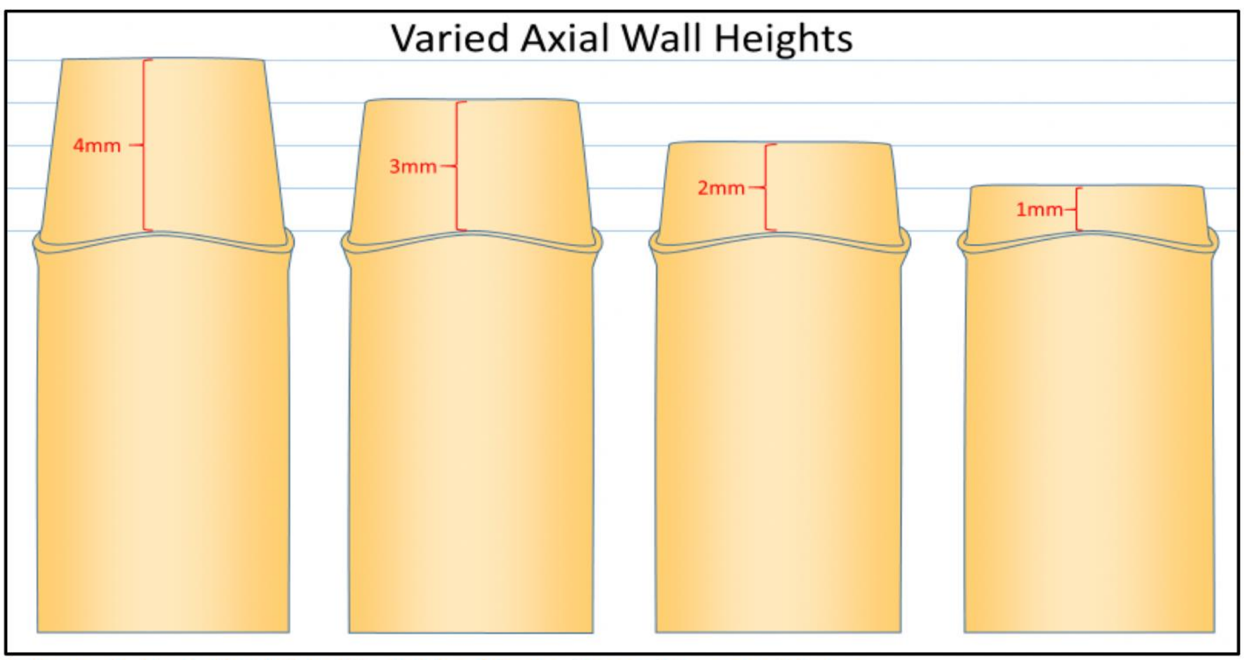

Figure 1. *Varied axial wall heights of 4mm, 3mm, 2mm, and 1mm*

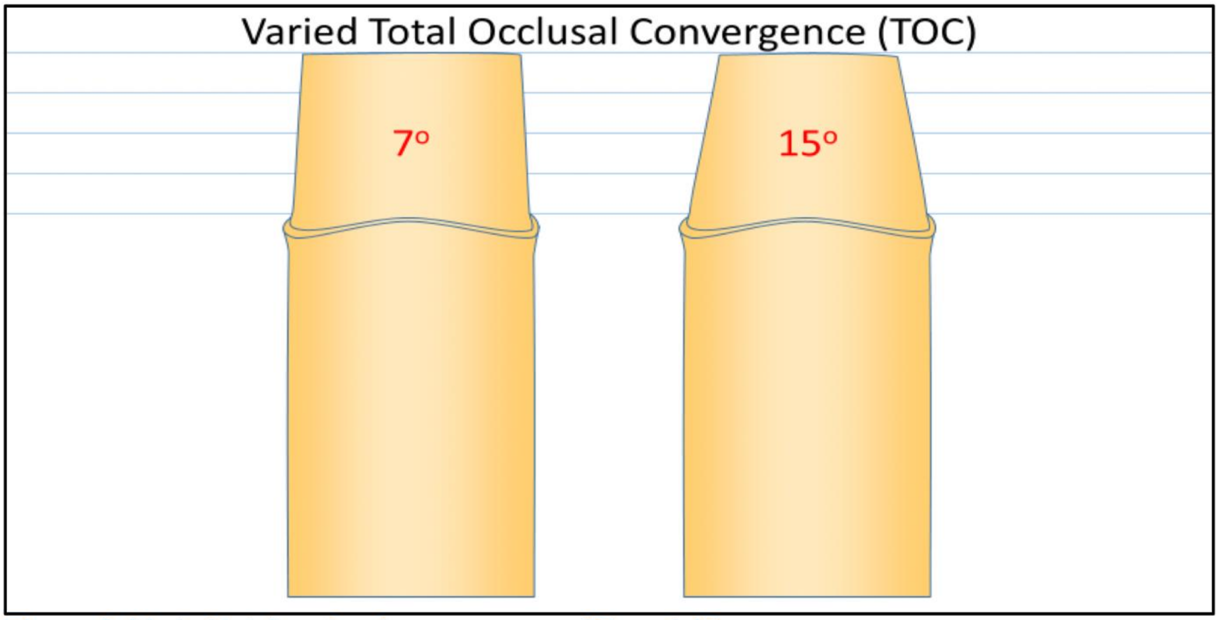

Figure 2. Varied total occlusal convergence of 7° and 15°

Each abutment had a corresponding 3Y-TZP zirconia (Sagemax NexxZr T, Washington, U.S.A.) crown fabricated [Figure 3]. Crowns were designed using Freeform Plus (3D Systems, Rock Hill, SC) CAD software with a uniform cement space of 80 micrometers and an occlusal surface angled at 45 degrees to the long axis of the prosthesis. Each crown had an axial wall thickness of 1.5 mm.

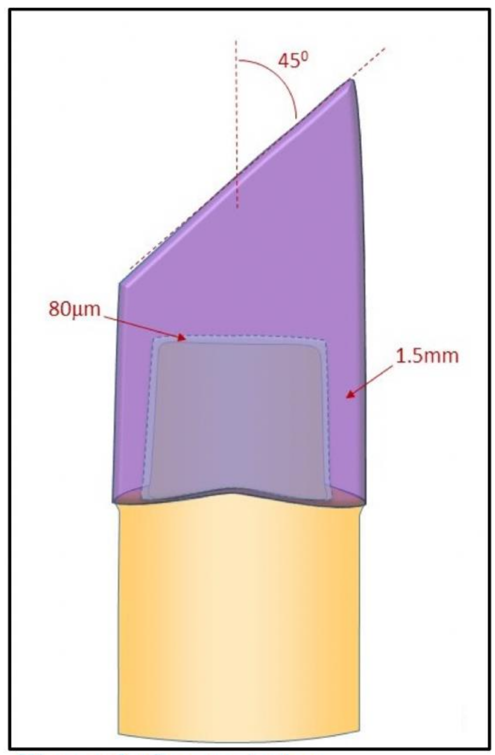

Figure 3. Crown design

Each crown and abutment were prepared for adhesive bonding by air abrasion with alumina oxide powder (50 microns) at 20-30 psi to the intaglio surface of crown and cameo surface of abutment, followed by steam cleaning, then dried with compressed, oil free air at 30 psi for 10 seconds. Next, ClearFil Ceramic Primer Plus (Kuraray America, Inc., New York, NY) was applied to each aforementioned surface per manufacturer instructions and allowed to react for 60 seconds, then dispersed with a mild stream of compressed, filtered, oil free air at 30 PSI for 2 seconds. Subsequently, Panavia V5 (Kuraray America, Inc., New York, NY) adhesive cement was applied to the intaglio surface of the crown, the crown was placed on the abutment and seated, using a 3D-printed resin crown seating index with 10 pounds of pressure for 30 minutes (Mannix Timer) [Figures 4, 5, & 6].

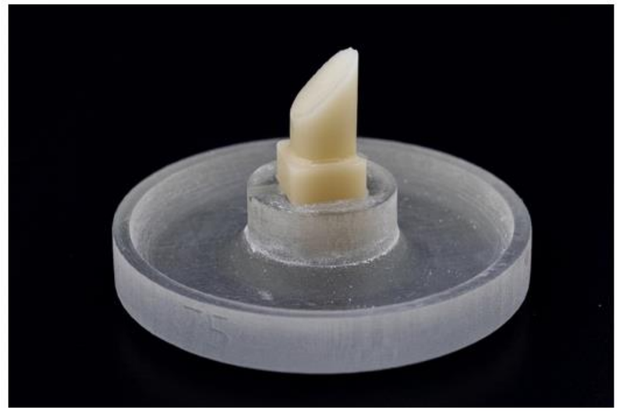

Figure 4. *Crown seating index base*

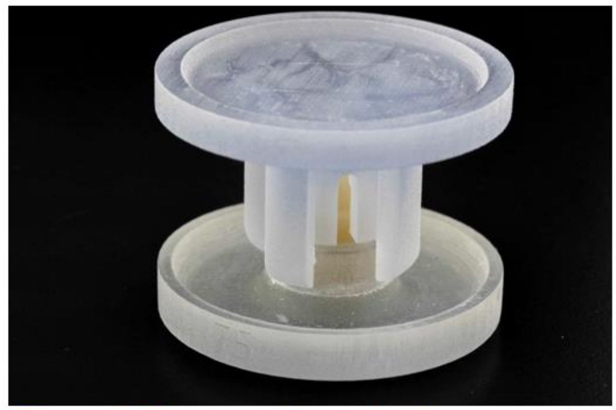

Figure 5. *Crown seating index top*

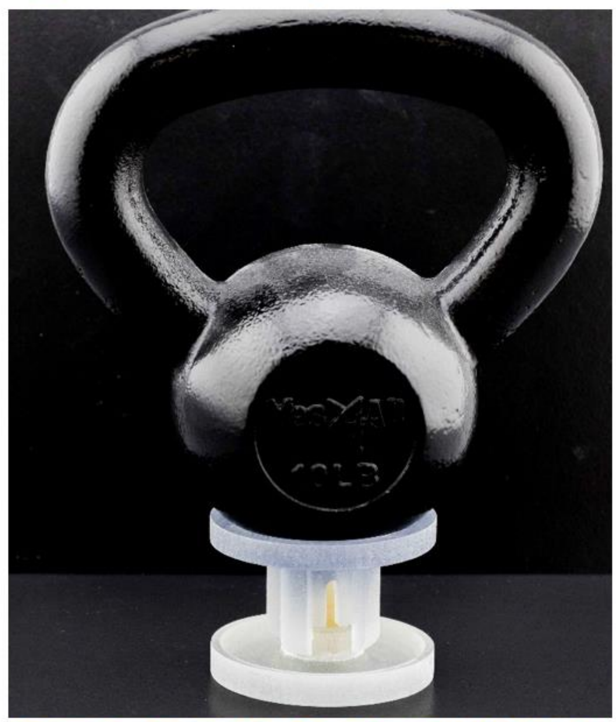

Figure 6. *Crown seating index with 10-pound weight*

Following cementation, samples were stored at 37^{o}C in 100% humidity for 24 hours, then thermocycled for 500 cycles in accordance with ISO/TS 11405 (Technical specification, 2003) standard for intermediate aging protocol prior to failure testing. Each 3Y-TZP abutment/crown sample was inserted into the testing apparatus: a custom-milled CoCr abutment holder bolted to the plate of an Industrial Series Instron Universal Testing System (Instron, Norwood, MA). Compressive force, advanced at one millimeter per minute, was applied to the flat surface of the crown, 45 degrees to the long axis of the sample [Figure 7], until failure was achieved. Failure modes included debonding or fracture of the crown, abutment, or both. The mode and load at which failure occurred was recorded.

The sample size of 10 per group provided 80% power to detect the following moderate effect sizes: 0.32 or approximately 0.64 standard deviations difference between means for the main factor of TOC (2 levels), and 0.38 or approximately 0.76 standard deviations difference among means for the main factor of AWH (4 levels). Interaction term was tested with a two-way ANOVA at the alpha level of 0.05 (NCSS PASS 2012). Post hoc testing was accomplished by using one-way ANOVA tests and Tukey's HSD tests on each AWH groups.

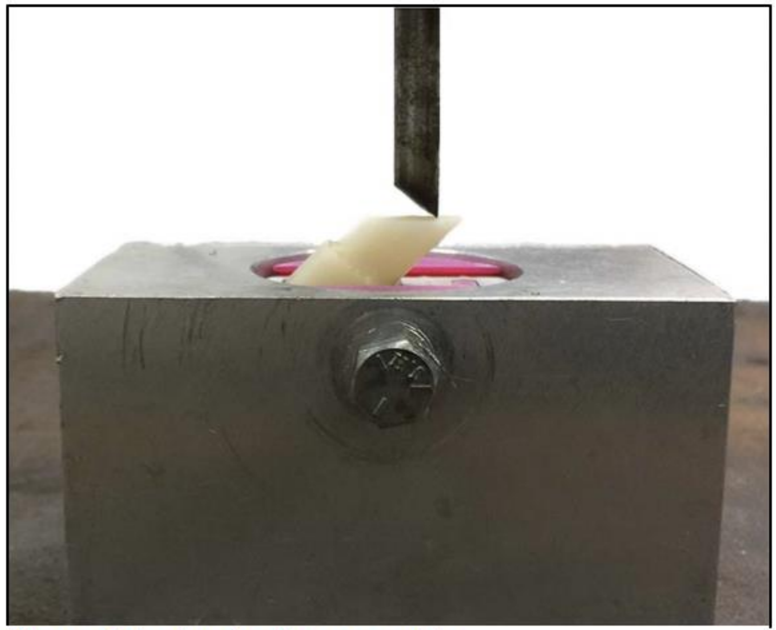

Figure 7. *Instron testing assembly*

RESULTS

The mode of failure was evaluated and recorded for each sample, the two primary categories being 1) the crown debonded or 2) the crown fractured. 98.75% of the crowns (79/80) debonded from their respective abutments and 1.25% of the crowns (1/80) fractured prior debonding [Table 1].

Sample Group	Dislodged Crowns	Fractured Samples
1mm x 7°	10	0
1mm x 15°	10	0
2mm x 7°	10	0
2mm x 15°	10	0
3mm x 7°	10	0
3mm x 15°	10	0
4mm x 7°	9	1
4mm x 15°	10	0
Total	79 (98.75%)	1 (1.25%)

Table 1. *Mode of failure*

SPSS computer software was used to calculate and tabulate the data. The load at failure for each test group are summarized [Table 2] and the range of the data is shown in a box plot [Figure 8].

Load at Failure [N]				
	1mm x 7°	**2mm x 7°**	**3mm x 7°**	**4mm x 7°**
1	325.5	443.1	1171.5	1422.9
2	440.1	1007.8	1589.5	1347.8
3	1565.0	746.5	1302.8	938.6
4	351.6	932.1	1095.1	1594.7
5	2288.9	1141.0	1249.9	1022.4
6	2097.8	537.9	2444.3	842.1
7	640.9	639.0	1246.7	1437.6
8	198.4	686.5	517.4	544.3
9	420.6	412.1	714.9	890.2
10	555.5	484.3	1262.3	954.1
	1mm x 15°	**2mm x 15°**	**3mm x 15°**	**4mm x 15°**
1	321.9	951.9	1075.2	949.3
2	266.3	747.7	1137.7	952.3
3	289.4	374.2	1135.3	447.7
4	640.6	480.4	501.1	507.3
5	205.0	423.3	1208.2	760.4
6	239.3	544.2	1048.5	643.3
7	178.8	346.5	547.1	761.2
8	495.3	521.8	565.1	581.9
9	16.6	929.3	518.6	1298.9
10	536.6	699.9	1027.8	1032.2

Table 2. *Amount of load [N] at failure point for each sample*

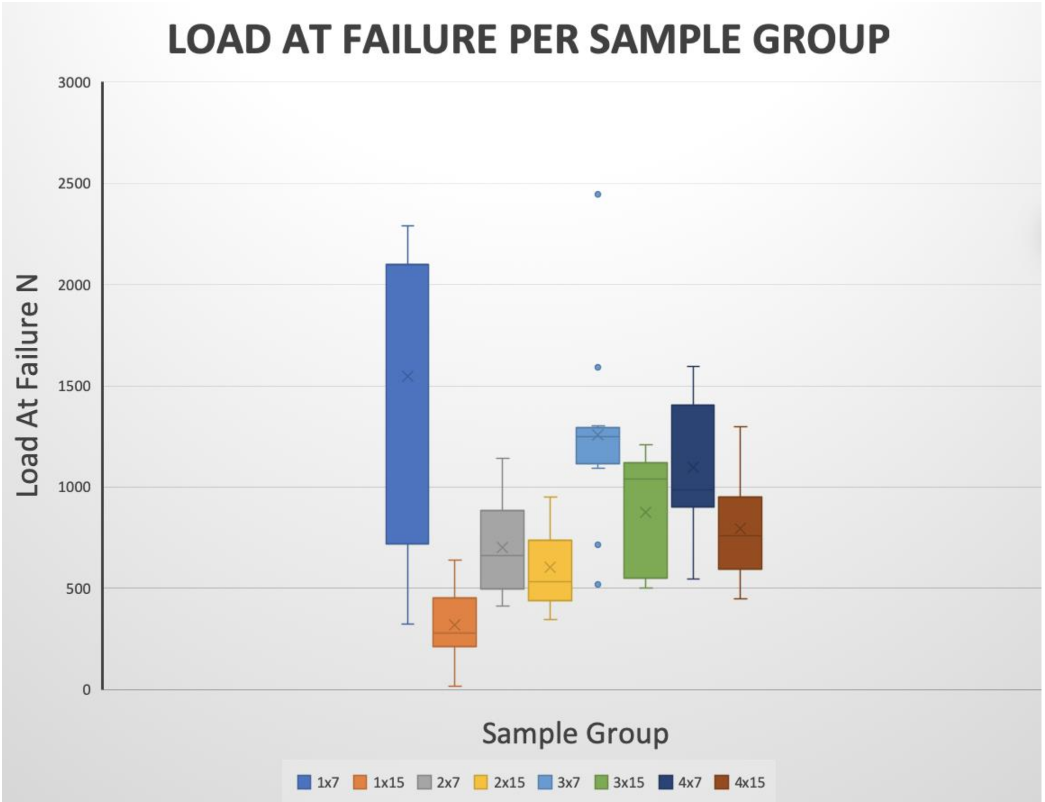

Figure 8. *Boxplots of load [N] at failure for each sample group*

Mean and standard deviations of the load at failure are listed in tables 3 & 4. The 3mm x 7° group had the highest mean load at failure at 1083.1 N, followed by 4mm x 7° group at 1026.1 N. The lowest mean load at failure was with the 1mm x 15° group at 301.67 N. The mean load at failure of 7° abutments was higher than the 15° abutments, with mean difference of 282.08 N.

Sample Group	Mean Load at Failure (N)	Standard Deviation (N)
1mm x 7°	878.36	776.66
2mm x 7°	681.66	273.97
3mm x 7°	1083.10	583.29
4mm x 7°	1026.10	319.00
1mm x 15°	301.67	206.24
2mm x 15°	601.86	219.67
3mm x 15°	873.84	297.90
4mm x 15°	763.52	269.33

Table 3. *Mean load [N] at failure by sample group*

Sample Group	Mean Load at Failure (N)	Standard Deviation (N)
1mm	590.01	627.21
2mm	641.76	245.13
3mm	978.47	463.38
4mm	894.81	317.34
7°	917.30	532.19
15°	635.22	325.28

Table 4. *Mean load [N] at failure by axial wall height and TOC*

Two-way ANOVA and one-way ANOVA were used to determine whether significant differences existed among the study groups (i.e. AWH and degree of TOC), followed by Tukey pairwise multiple comparisons at 95% confidence interval, which were performed to determine which AWH group at a given TOC group significantly differed from the other.

	7º	15º	Total
1mm	878.36[a]	301.67[1b]	590.01
2mm	681.66	601.86	641.76
3mm	1083.10	873.84[2]	978.47
4mm	1026.10	763.52[2]	894.81
Total	917.30[A]	635.22[B]	

***Table 5**. Results of Post Hoc Analysis*

Different capital letters ([A, B]) indicate statistically significant difference between TOC groups but no difference within TOC groups
Different numbers ([1, 2]) indicate significant difference within same TOC group (1mm significantly different from 3mm/4mm
Different lower-case letters ([a, b]) indicate statistically significant difference within same AWH group (1mm).

According to the two- way ANOVA, AWH and TOC are both statistically significant factors of the load required to make the crown fail; however the interaction between the AWH and TOC on mean load at failure is not significant. The mean values for load at failure of the 7°TOC group as a whole is statistically different than the 15°TOC group as a whole. Within the 7° TOC group, the mean load at failure between the different AWH groups was not statistically significant. This contrasts from the 15° TOC group which had a statistically significant difference between the 1mm AWH and the 3/4mm AWH's. There is no statistically significant difference between the 3mm AWH and the 4mm AWH for the 15° TOC. When evaluating the 1mm AWH group, there is a statistically significant difference in the mean load at failure between 7° and 15° TOC. There is no difference when evaluating the other AWH groups between the various degrees of TOC.

DISCUSSION

An important consideration in evaluating the results of this study is the standard deviation values for the various data points. Many of the standard deviation values were very large relative to the mean load at failure for their respective group. In fact, some were more than half the mean load at failure. This analysis of the data led our research team to a discussion focused on the large variability seen particularly in the shorter axial wall height groups. It was during this analysis and discussion that we realized that our design had inadvertently introduced a confounding variable. In an attempt to keep all factors unchanged, only varying the axial wall height, we had designed to keep the overall crown height the same for all AWH groups. In doing this, however, we altered cusp height. This change effectively results in a longer lever-arm when force is applied, thereby varying the amount of force placed on the cusp. Clinically, an operator would never electively choose short AWH, rather it would be dictated by the available restorative space, thus a relatively constant CH with respect to the restorative material would exist in the clinical setting. This important discovery brings into question the validity of this study's data but is an important step in the search to answer this relevant clinical question. A constant CH should be used for consistent results if a similar study is performed.

The purpose of this study was to quantify the effect that AWH and degree of TOC have on the resistance to dislodgement of milled 3Y-TZP zirconia crowns bonded to milled 3Y-TZP zirconia custom implant abutments. This data demonstrates that statistically significant different forces are required to dislodge the crowns with varied AWH and TOC. The null hypothesis was that there would be no statistically significant difference in the amount of force required to dislodge 3Y-TZP zirconia crowns bonded to 3Y-TZP zirconia custom implant abutments when the AWH of the abutments and the TOC of those axial walls varied. Therefore, the null hypothesis was rejected. I do so with caution as I try to extrapolate clinical significance knowing that the data could have been different if I had controlled for the cusp height.

Important factors to consider in the results of this study are the mode of failure and the mean load required for failure. All but one of the samples failed due to debonding of the crowns (98.75%) rather than fractured (1.25%) [Table 1]. Considering the maximum bite force (mean = 354 N) generated in human mastication (Takaki *et al.*, 2014) and during sleep associated bruxism (mean = 415 N) (Nishigawa *et al.*, 2001), the 1mm and 2mm AWH groups of both TOC groups would possibly be at greater risk of the crowns debonding. The clinical application the data supports is the potential need for 3mm of AWH and a TOC of up to 15° when bonding a 3Y-TZP zirconia crown to a 3Y-TZP zirconia abutment with resin cement. This will create a crown/abutment interface to be more than adequate to resist dislodging forces typically produced in the oral environment.

This study was designed to simulate the most unfavorable condition *in* vitro in which a 3Y-TZP zirconia crown bonded to a 3Y-TZP zirconia implant-supported abutment could receive a load *in vivo*. Particularly, a load applied at 45 degrees to the long axis of the restoration with the lever arm (approximately 14mm from the point of rotation) reaching the upper limit of what would be encountered clinically. In clinical situations, the crown height is dictated by the required material thickness. This is commonly a required 1-2mm required minimum thickness, in addition to the needed height of the abutment. Even in situations with limited restorative space, it is unlikely to have a 1mm tall abutment but require a 14mm tall crown, which further demonstrates that this study generates more extreme conditions than would likely be encountered *in vivo*.

The results of this *in vitro* investigation indicated that there were no statistically significant differences in the force required to dislodge or fracture the crown for 7° TOC group. At first glance it seems this data is in opposition to a previously proven and predictable pattern that TOC and AWH have significant impact on mean load of failure, and are critical requirements for retention and resistance form (Goodacre *et al.*, 2001) in regards to crowns luted to natural teeth. One may be tempted to conclude the reason there was no statistically significant difference as the AWH varied was due to the bonding of the 3Y-TZP crown and abutment. However, when considering the large standard deviation for this data set, it is reasonable to conclude there was no significant difference due to a wide variance of force needed to dislodge or break the crowns and the data of this group told us very little. The data does not support being able to overcome inadequate AWH and TOC by chemically bonding a 3Y-TZP crown to a 3Y-TZP abutment.

It is also important to remember that like many *in vitro* studies, *in vivo* conditions cannot be completely duplicated and the results of this study do not necessarily associate with *in vivo* conditions. A variety of factors can lead to restoration failure. Examples are the frequency, duration, and vector of the load applied to the crown as well as degradation of the resin bond, or salivary contamination when the bonding initially takes place. It would be impractical to account for all these in an *in vitro* investigation. Further research is needed to examine the mechanisms of failure of 3Y-TZP zirconia crowns cemented to 3Y-TZP zirconia custom implant abutments. Improved methods and protocols may lead to more significant data with smaller standards of deviation.

CONCLUSION

The biggest finding of this study was that due to the design an accidental variable was introduced but wasn't accounted for calling into question the data obtained. Overall, it took more loading force to dislodge the 7° TOC groups than the 15° TOC groups; this difference was statistically significant. Within the 15° TOC group, the force required to cause the 3/4mm AWH groups to fail was statistically significantly more than the 1mm AWH group. Finally, within the 1mm AWH group, the force required to cause the 7° TOC abutments/crowns to fail was statistically significantly more than the 15° TOC abutments/crowns.

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DISCLOSURES

The opinions or assertions contained herein are the private ones of the author and are not to be construed as official or reflecting the view of the Uniformed Services University of the Health Sciences, the United States Air Force, the Department of Defense, or the United States Government. The author does not have any financial interest in any commercial products or services that are discussed in this publication.

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