Repairability of Anterior Full Coverage High Translucent Zirconia Restorations Following Endodontic Access Preparation

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ABSTRACT

Purpose: The purpose of this in vitro study was to evaluate and compare the static strength and endurance limit of full coverage anterior restorations—fabricated from two high translucent monolithic zirconia with different yttria concentrations—before and after endodontic access and repair.

Materials & Methods: Two sets of fifty monolithic anterior crowns were milled from high translucent "HT" and super high translucent "Super HT" zirconia blanks, respectively. All crowns were autoclaved to simulate intraoral aging, and were then conventionally cemented onto dies milled out of a dentin substitute material, NEMA G10. The crown specimens consisted of four zirconia groups: Intact HT, Repaired HT, Intact Super HT, and Repaired Super HT. The repaired crowns were prepared with a standardized endodontic access and repaired with a direct composite resin restoration. One set of crowns (n = 10/group) were loaded to failure to determine the static strength, while the remaining crowns (n = 15/group) were cyclically loaded for 50,000 cycles to determine the endurance limit. Data were analyzed using one-way ANOVA / Tukey's post hoc test ($\alpha = 0.05$) and independent samples t-test.

Results: The static strength and endurance limit of the four aforementioned groups were measured and calculated. Statistically significant difference in static strength was observed not only between HT and Super HT crowns but also between Intact and Repaired crowns: the HT crowns had higher static strength than the Super HT crowns, and the Repaired crowns performed better than the Intact crowns. There was also a statistically significant difference in endurance limit between HT and Super HT crowns, with the HT crowns showing higher endurance limit than the Super HT crowns. However, no statistical difference in endurance limit was noted between the Intact and Repaired Super HT crowns although the Repaired HT crowns exhibited higher endurance limit than the Intact HT crowns.

Conclusion: The concentration of yttria content, thereby degree of translucency, had a significant effect on the static strength and endurance limit of anterior monolithic zirconia restorations: HT crowns exhibited lower yttria content but superior strength than Super HT crowns, for both Intact and Repaired groups. The endodontic access preparation did not seem to negatively affect the static strength and endurance limit of HT and Super HT zirconia crowns. Repairment of high translucent and super high translucent anterior zirconia crowns following endodontic access preparation may be an alternative treatment option.

KEYWORDS**:** static strength, endurance limit, monolithic, milled, root canal treatment

INTRODUCTION

Approximately, 20% to 50% of endodontic procedures are performed through full coverage restorations.[1,2] These clinical treatments often present a dilemma: whether repair or replacement of an endodontically accessed crown is the best practice.[1] This controversy was reflected through a recent survey, in which most dentists indicated their treatment rationale was perhaps prejudicially based on the notion that repaired crowns might have shorter lifespans than intact or new crowns (**Kanzow**). Although clinical data on the longevity of repaired crowns is scarce, one retrospective clinical study reported that the median survival time for repaired crowns was 9.7 years and concluded that endodontically accessed crowns repaired with composite extended the lifespan of single crowns (**Wiegand**). Contrarily, most in vitro studies have demonstrated that the integrity, strength, and fracture resistance of repaired crowns were more compromised upon loading than new or intact crowns ([1,15]**Queblawi, Sutherland**).

Currently, there is no recommended guideline on how endodontically accessed crowns may be best restored. In general, the decision to repair or to replace an endodontically accessed crown is based on one's past experiences or teachings and is largely dependent on the size of the defect or endodontic access as well as the age, marginal integrity, and material composition of the original restoration (**Kanzow**). Other factors like the repair material and its physical properties, cement chemistry and cementation method, and rotatory burs such as diamond or carbide used for preparation and finishing may also contribute to the longevity or brevity of a repaired all-ceramic crown.[3] Furthermore, the advent of new dental materials like high translucent zirconia with high yttria concentration has made the dilemma—whether to repair or to replace—even more relevant and challenging.

Today's high translucent zirconia are robust, polycrystalline ceramics that offer excellent esthetics, high strength, and anti-corrosion properties. The physical properties of these new zirconia are dependent on the chemistry and concentration of dopant, grain size, distribution of intrinsic flaws, polymorphic stability, and processing techniques (10). For example, "Zolid fx white" (Amann Girrbach) appears more translucent than "Zolid ht+ white" (Amann Girrbach). This is because "Zolid fx white" contains a higher concentration of yttria dopant than "Zolid ht+ white" (9.15-9.55 molar % versus 6.7-7.2 molar %, respectively). This high concentration of yttria alters zirconia grain size, resulting in the reduction of grain boundaries such that less light is scattered, and therefore inherent birefringence are diminished.[10] Ultimately, an increase in translucency is experienced when viewed under natural lighting. Furthermore, increasing the yttria content stabilizes the cubic structure, making it the predominant phase for most high translucent zirconia at room temperature (10,11). In comparison, traditional zirconia is composed of predominately tetragonal phase, which is stabilized with 3 molar % yttria at room temperature, creating the popular yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP). Although most zirconia can be toughened via additives and heat treatment, some high translucent zirconia, even after proper sintering, have diminishing strengths along with reduced abilities to exhibit transformation toughening (10,11). In contrast, transformation toughening of traditional 3Y-TZP zirconia has a higher probability to occur than cubic-rich zirconia, through stress-induced destabilization of tetragonal structures, in which transformation to the monoclinic phase is accompanied by large volumetric change (4,6,7,8,10,11). Ultimately, this precipitated volumetric expansion manages to reduce the applied stresses at the crack wake-zone by either inhibiting or deflecting meandering cracks from further propagation.[4,6,7,8,10,11] Although endodontic access through porcelain and glass-ceramics is known to cause crack propagation and edge chipping, perhaps high translucent zirconia is expected to respond differently.[12,13] Arguably, past studies have shown that factors such as bur type, bur grit, motor speed, and operator's force during grinding and access preparation, can contribute to some degree of micro-damage, thus predisposing the zirconia to unnecessary, stress-induced transformation toughening (14, **Yin 2003**). On that basis, controversy remains regarding the repairability of high translucent zirconia after the creation of an endodontic access.

Although in vitro studies on the performance of repaired crowns have been repeatedly investigated, these endeavors were mostly limited to posterior restorations rather than anterior restorations (1,15,**Qeblawi**, **Bompalaki).** This study focuses on anterior monolithic zirconia crowns and investigates whether their strength and endurance limit can be affected by endodontic access preparation and variation in zirconia translucency—or thereby variation in cubic content. The null hypotheses were: (1) super high translucent "Super HT", anterior monolithic zirconia crowns comprised of high yttria content, possessed similar static strength and endurance limit as high translucent "HT", anterior monolithic zirconia crowns comprised of lower yttria content, regardless of whether crowns have been repaired; and, (2) repaired anterior monolithic zirconia crowns following endodontic access possessed similar static strength and endurance limit as intact anterior monolithic zirconia crowns, irrespective of their yttria content.

MATERIALS & METHODS

***Master Die and Jig Fabrication*:** A typodont tooth (maxillary central incisor) was prepared following the manufacturer's recommendations: 1.0 mm incisal reduction, 0.5 mm chamfer finish line, and 1.0 mm uniform axial reduction (Clinical guide, Amann Girrbach). It was then scanned in an optical scanner (D900, Dental System 2015, 3Shape, Copenhagen, Denmark), from which the die's digital preparation was merged with the digital design of a cylindrical jig made to intimately fit with the mounting table (Fig. 1). The die-jig compound was milled out of NEMA (National Electrial Manufacturers Association) G10 (TriStar Plastics Crop., Shrewsbury, MA, US) as one unit and contained an anti-rotational feature for securing to a stable and repeatable position during load testing (Fig. 2a). Natural teeth were not used in this study to avoid heterogeneity of biologic samples.

Crown Fabrication: The crowns were divided into 2 groups: HT and Super HT (n = 20/group for static strength test, n = 30/group for endurance limit test). The unprepared and prepared typodonts were scanned using a desktop scanner (Ceramill Map 400, Amann Girrbach, Charlotte, NC, US). The restorations were virtually designed using CAD software (Exocad, Darmstadt, Germany), to mirror the contour of the unprepped typodont. Two sets of fifty crowns were milled from HT zirconia and Super HT zirconia blanks, respectively, using a 5-axis milling unit (Ceramill Motion 2, Amann Girrbach, Charlotte, NC, US). They were sintered at 1450 °C for 9 hours and 45 minutes on the standard cycle (Ceramill Therm, Amann Girrbach, Charlotte, NC, US). All crowns had identical contour.

Hydrothermal Aging (autoclaving): All crowns were hydrothermally aged, following the protocols by Camposilvan et al. and Nakamura et al. to simulate low temperature degradation (LTD)-inducing conditions.[18,19] The crowns were immersed in distilled water and autoclaved (M11 Ultraclave, automatic sterilizer, Midmark, Traverse City, MI, US) at 134 °C for 1 hour under 2 bar, which corresponds to 2-4 years intraorally (ISO13356, 2008).[18,19]

Crown Cementation: Following manufacturer's recommendations, conventional luting with glass ionomer cement were performed (Clinical guide, Amann Girrbach). The intaglio surfaces of the crowns were air-abraded with 30-50 micron aluminum oxide at 2 bar pressure, until a matte surface was produced. The crowns were cleaned with alcohol, air-dried, and cemented on their respective die-jigs with Rely X Luting

Plus Automix Cement (3M, ESPE, St. Paul, MN, US). The crowns were seated with finger pressure and full seating was confirmed under a stereomicroscope (Fig. 2b).

Endodontic Access Preparation**:** Specimens were allocated into 4 subgroups: Intact HT, Repaired HT, Intact Super HT, and Repaired Super HT. For Repaired groups, a standardized endodontic access was prepared. A fine grit round end tapered diamond bur (8856.31.016, Brasseler, Savannah, GA) in a high-speed handpiece was used under copious water irrigation.[15] A vacuum formed matrix with an outlined endodontic access was fabricated, and served as a transfer template for repeatable endodontic access (Figs. 3a-c). All endodontic access preparations were completed by the same endodontic resident. A new diamond bur was used for each access preparation.

Access Repair: The accessed crowns were repaired using a porcelain repair system (Intraoral Repair Kit, Bisco, Schaumburg, IL, US) and a resin-based composite (Z100 MP Restorative, shade A1, 3M ESPE, St. Paul, MN, US), following manufacturer's instructions. For each crown, the access preparation was beveled 0.5 mm at a 45 degree angle. Next, porcelain etchant (9.5% HF) was applied for 90 seconds, rinsed with copious amounts of water, and air-dried. Then, porcelain primer was applied for 30 seconds and air-dried, which is followed by placement of 1-2 coats of Z-Prime Plus, air-drying, and 5 seconds light-curing (Valo, Ultradent, South Jordan, Utah, US). The composite was placed no more than 2.0 mm increments to reduce polymerization shrinkage (Fig. 3d). The repaired site was adjusted, finished with fine football diamond burs, and polished (Enhance & Pogo Finishing and Polishing System, Dentsply, York, PA) flush to the adjacent zirconia.

Material Properties Testing (static strength and endurance limit): An electrodynamic testing instrument (ElectroPuls-E3000, Instron, Norwood, MA, US) was used. Loading of specimens was directed at a 45° angle off the long axis of the tooth (Fig. 4). The loading piston contacted the lingual surface of each crown in the center, between the cingulum and incisal edge. In the repaired crowns, the loading piston contacted the junction between the composite and zirconia. Two properties were measured: "static strength", representing the load to failure, and "endurance limit", representing the load value below which an infinite number of loading cycles can be applied without causing failure.

Static strength testing: For static strength, ten specimens were tested from each subgroup: Intact HT, Repaired HT, Intact Super HT, and Repaired Super HT. These specimens were loaded to failure.

Endurance limit testing: For each group, the starting force value was determined by using ½ of the mean static strength in accordance to ISO14801, which served as the estimated baseline for cyclic loading.[20] The loading frequency was set at 15 Hz, instead of the intraoral loading frequency of 1.5Hz, to expedite the data collection without significantly altering fatigue outcomes.[21] Cyclic loading occurred over 50,000 cycles, equivalent to 3 months of clinical service.[21] The loading range, representing the amplitude for cyclic loading, was calculated according to ISO14801.[20] The step width, defined as the degree to which the baseline load value will change between consecutive cycles, was set at 20% of the estimated maximum endurance load ($d = 20\%\ \sigma_o$,where d is the step width and σ_o is the estimated endurance load), as described in ISO14801.[20] If the first specimen survived after 50,000 cycles, the new baseline load value for the next specimen was increased by 20% and the loading range was adjusted accordingly. If the specimen failed during the 50,000 cycles, the new baseline load value for the next specimen was decreased by 20% and the loading range was adjusted accordingly. If the specimens survived for the first three consecutive tests, the step width was increased to 35% until the first failure, at which point the step width was reduced back to 20% for the remainder of the specimens in that group, regardless of survival or failure. This staircase method continued until all specimens from one subgroup were tested. The same protocol was repeated for the remaining three subgroups. The endurance limit and standard deviation were determined using the following equations:

$$\sigma = X_o + d\left(\frac{\sum i n_i}{\sum n_i} \pm 0.5\right)$$

$$SD = 1.62d\left(\frac{\sum n_i \sum i^2 n_i - (\sum i n_i)^2}{(\sum n_i)^2} \pm 0.029\right)$$

X_0 is the lowest stress level considered in the analysis and d is the fixed stress increment or step width. To determine σ, the analysis of the data were based on the least frequent event (failures vs survivals). The negative sign is used when the analysis is based on failures; otherwise the positive sign is used. In the second equation, the lowest stress level considered is designated i = 0, the next i = 1, and so on, and n_i is the number of failures or survivals at the given stress level.[20]

Statistical Analysis: Statistical analyses were performed with JMP statistical software (SAS, Cary, NC, USA). A one-way analysis of variance (ANOVA) followed by Tukey HSD ($\alpha = 0.05$) were conducted to detect any significant difference between the groups. An Independent Samples t-test was used to further compare, collectively, HT zirconia vs. Super HT zirconia, and Intact crowns vs. Repaired crowns.

RESULTS

The static strength was significantly affected by the distinct yttria concentrations of high and super high translucent zirconia, as well as the condition of the crowns, being either intact or repaired *($p < 0.001$)* (Fig. 5a). Specifically, the Repaired HT group has significantly higher static strength than all other groups. Furthermore, when HT crowns were compared with Super HT crowns, crowns with lower yttria concentrations exhibited significantly higher static strength than crowns with high yttria concentrations *($p = 0.0056$)* (Fig. 5b). In contrast, irrespectively of yttria concentration, repaired crowns performed statistically better in static strength than intact crowns *($p < 0.001$)* (Fig. 5c).

Crowns from the Repaired HT group demonstrated significantly higher endurance limit than all other groups *($p < 0.001$)* (Fig. 6a). Furthermore, when HT crowns were compared with Super HT crowns, a similar trend of static strength was observed: crowns with lower yttria concentrations exhibited significantly higher endurance limit than crowns with high yttria concentrations *($p < 0.001$)* (Fig. 6b). However, under fatigue the endurance performance of repaired crowns was not statistically better than intact crowns *($p > 0.05$)* (Fig. 6c).

DISCUSSION

Based on the findings obtained from this study, the first null hypothesis was rejected. Super HT, anterior monolithic zirconia crowns comprised of high yttria content, exhibited statistically significant reduction in static strength and endurance limit than the HT, anterior monolithic zirconia crowns comprised of lower yttria content. Furthermore, the translucency of the zirconia appeared to be inversely correlated with its mechanical properties—the higher the translucency, the lower the static strength and the endurance limit of the crowns. These findings seem to augment past studies, in which the strength of high translucent zirconia is typically less than traditional zirconia (i.e., 3Y-TZP).[10,11] Theoretically, stabilization of more cubic phase at room temperature is a direct consequence to an increase in yttria concentration. Because of this, past studies have argued that zirconia with more cubic phase are not only more brittle than traditional zirconia, which consists primarily of tetragonal phase, but also suffers from the inability to exhibit transformation toughening.[4,5,10,11]

Based on the findings obtained from this study, the second null hypothesis was partially rejected. Although the repaired crowns performed statistically better in static strength than the intact crowns, the endurance limit of the repaired crowns performed similarly as the intact crowns. Although this result is counterintuitive, past studies have found similar outcomes **(Wiegand, 13)**. However, additional studies are needed to further verify and explain why repaired crowns performed similarly to intact crowns under fatigue.

Several factors were carefully considered when this study was designed: material composition of the die-jig compound, endodontic access preparation technique, cementation methods, and zirconia aging processes.

From past studies, it is evident that the abutment substrate or the die-jig material, particularly its elastic modulus, can affect the fracture resistance of ceramic restorations ([9],**Chen, Yucel**). One in vitro study demonstrated that using a rigid metal die with a higher elastic modulus, compared to an epoxy die with a lower elastic modulus, resulted in a higher fracture resistance of a zirconia core—therefore, a die that mimics the elastic modulus of dentin was recommended (**Yucel**). In this study, the zirconia crowns were cemented on die-jig compounds that were milled from woven glass fiber-filled epoxy resin, known as NEMA G10. Because NEMA G10 have comparable elastic modulus (18.6 GPa) and stress-strain curve to those of hydrated dentin (15-20 GPa), NEMA G10 was selected as a "dentin substrate" substitute to enhance the correlation between the laboratory and in vivo behavior of zirconia and to mimic a clinically relevant condition.[9,22]

It was also evident that from past studies, how an endodontic access preparation was performed could affect a crown's strength and toughness. In this study, the endodontic access preparations were performed using a fine grit diamond bur in a high-speed handpiece under copious water irrigation. Diamond burs, compared to carbide burs, showed a higher efficiency when cutting zirconia.[24] Fine grit diamonds, compared to coarse grit diamonds, produced less defects and chipping.[25] However, these burs were frequently the source of stresses and heat, both of which could often contribute to the tetragonal-to-monoclinic transformation, resulting in unwarranted transformation toughening (14, **Subasi**). For example, past studies using X-ray diffraction (XRD) analysis have shown that for specimens made from 3Y-TZP zirconia, a reduction in tetragonal peaks was often associated with an increase in monoclinic peaks after the zirconia was adjusted with operatory burs in a dental high-speed handpiece (14, **Subasi**). Thus, using a high-speed handpiece to minimize preparation time while irrigating with copious water to reduce heat were recommended to lessen the "premature" tetragonal-to-monoclinic phase shift.[25] However, further studies are needed to measure and analyze the benefits of transformation toughening and how this information can be extrapolated from minor occlusal adjustments to more involved procedures, such as an endodontic access preparation.

A recent in vitro study demonstrated that whether crowns were luted or bonded with cements of various chemical and mechanical properties, such as compressive strength, there was no significant impact on the fracture resistance of monolithic zirconia crowns (23,30). Thus, the zirconia crowns in this study were luted, as opposed to bonded, onto their respective dies. The master die was prepared following the manufacturer's recommendations, all crowns were cemented using glass ionomer cement, and none of the crowns demonstrated cementation failure prior to crown failure during the study.

Lastly, autoclaving zirconia has been advocated to simulate low temperature degradation (LTD)-inducing conditions (18,19). In accordance to an in vitro study, autoclaving zirconia can decrease the fracture resistance of monolithic 3Y-TZP zirconia crowns (18). Theoretically, zirconia ceramics containing high amounts of tetragonal phase is more susceptible to LTD than zirconia ceramics containing high amounts of cubic phase.[11,19] For example, XRD analyses in recent studies have demonstrated autoclaving high translucent zirconia to have no significant effect on spontaneous transformation from cubic to monoclinic phases and consequently no effect on the fracture resistance (**Pereira, Prado**). Further investigation is needed to understand how high cubic zirconia is affected by phase transformation that occurs as a consequence of LTD.

Other limitations that might have affected the outcomes of this study included the loading apparatus and the number of loading cycles. In this study, the loading apparatus for distribution of loads onto the crown-die-jig compound was a 3mm round-ended stainless-steel piston. An in vitro study demonstrated that the piston material could influence ceramic fracture behaviors (**Weber**). Although natural tooth would be more appropriate, it is also prone to fracture and is difficult to standardize. Perhaps, a ceramic piston (lithium disilicate) is more befitting since its elastic modulus is similar to that of enamel (**Weber**). Another limiting parameter was the crowns were cyclically loaded for a maximum of 50,000 cycles, equating 3 months of intraoral use (21). Longer loading cycles, although extremely time consuming, could be more revealing on how high translucent zirconia responds to long-term fatigue. Futhermore, the two aging processes, LTD fatigue and cyclic fatigue, were not the same duration; autoclaving corresponded to 2-4 years intraorally, whereas cyclic loading of 50,000 cycles corresponded to 3 months. Perhaps, by matching the corresponding time of the two aging processes, one may have better insight for the repairability of high translucent zirconia crowns following endodontic access preparation.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions can be drawn: 1) the translucency affected the physical properties of zirconia; the higher the translucency, the lower the static strength and the endurance limit; 2) the endodontic access preparation did not negatively affect the static strength and endurance limit of high translucent and super high translucent zirconia crowns; 3) replacement of high translucent and super high translucent anterior zirconia crowns does not seem to be clinically necessary or required following endodontic access preparation; and, 4) repairment of high translucent and super high translucent anterior zirconia crowns with composite may be an alternative treatment option.

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